Stochastic Assessment of Voltage Unbalance Mitigation by Battery System in case of Single-Phase Solar Generation

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ABSTRACT OF THE
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The political decisions and environmental problems apply a pressure on the research to utilise environmentally friendly energy sources and bring them to masses. However, the vast spread of renewable energy generation, such as solar power, adds an additional strain to electric power grid and damage the quality of the supplied electrical energy. In this thesis, stochastic assessment of the voltage unbalance mitigation by home battery system in low voltage grid with single-phase solar generation is analysed.

The stochastic voltage unbalance assessment method based on Monte Carlo Simulation technique was utilised for two algorithms: time independent and time dependent. Both models were presented and results of each were compared. Three different battery phase connection strategies were modelled and voltage unbalance mitigation efficacy of each was evaluated. Three low voltage distribution grids are considered - rural, intermediate and urban - each grid representing different regions in Finland. The voltage unbalance at different solar and battery penetration levels was assessed and the most efficient battery connection strategy was revealed. Lastly, various aspects of the topic were discussed in the end.

Keywords: Voltage unbalance, Photovoltaics, Battery energy storage system, Stochastic assessment, Monte Carlo Simulation

Preface

I would like to extend my gratitude towards Professor Matti Lehtonen and the Electric Power Engineering group of Aalto University.

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Verner Püvi

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Symbols and abbreviations

Symbols

$\underline{i}_m^{(2)}$	column vector of negative sequence current
$S_{PV,max}$	maximum value of solar power generation in a grid
$S_{demand,max}$	maximum value of load power in a grid
$v^{(0)}$	zero sequence voltage
$v^{(1)}$	positive sequence voltage
$v^{(2)}$	negative sequence voltage
v_a	phase a voltage
v_b	phase b voltage
v_c	phase c voltage
$\underline{v}_n^{(2)}$	column vector of negative sequence voltage
$\underline{Z}_{nm}$	square matrix of mutual impedance
Z_{XFMR}	transformer impedance
Z_{FEED}	feeder impedance

Operators

a	phase shift operator $= 1 \cdot \angle 120°$.

Abbreviations

BESS	battery energy storage system (home battery)
HC	hosting capacity
IN	intermediate (region)
PDF	probability distribution function
PR	predominantly rural (region)
PU	predominantly urban (region)
PV	photovoltaic (solar array)
VU	voltage unbalance

1 Introduction

1.1 Background

Over the past 150 years electrical energy has become an indispensable part of the world. During that time, electrical engineering gave birth to many other industries, such as electronics and computer engineering. Electricity have changed from a rarity to commodity and is used in wide range of applications. Daily life is influenced by electricity so much that it has become almost impossible to imagine a day without it. Today it is obvious that reliable and cost effective power system is necessary for successful development of every society.

The electric power system plays an important role in building electrical energy infrastructure. However, today it is being challenged by new trends and big changes need to be done in the future. The global warming forces humanity to find new ways of generating electricity in a more sustainable and environmentally friendly way. Policymakers have taken the decision to lower the carbon-based energy source share in electrical energy production and enforce the utilisation of renewable energy sources, such as solar power [1, 2]. The share of solar power generation has grown significantly in recent decade and the further growth is expected in Finland and the rest of the world [3, 4]. The modern power system is built around the fossil fuel utilisation and is embedded to fossil fuel generated electrical energy supply chain [5]. However, the power system must be a binding link between the all types of energy generation and consumption.

Power system should be reorganised to be capable of hosting renewable energy sources and be able to tackle the problems caused by high penetration of distributed energy generation [6]. It is the responsibility of the power engineers to analyse the consequences of distributed generation and provide solutions for solving emerging problems. One of the most adverse impacts on power system operation caused by renewable energy sources, such as single-phase-connected solar, is voltage unbalance in low voltage residential grid [7].

1.2 Objectives

The thesis aims to meet three targets:

1. Develop a stochastic framework for voltage unbalance assessment for time independent and time dependent algorithms.

2. Compare the results of time independent and time dependent algorithms.

3. Present the possibilities of mitigating voltage unbalance by introducing a battery energy storage system.

The stochastic framework allows to estimate the voltage unbalance with probabilistic input variables and the results can be statistically analysed. The two algorithms can assess voltage unbalance in same grid. The time independent model does not require information about customer load and solar generation/load demand time variation pattern. On the other hand, time dependent model calculates the voltage unbalance based on time series of hourly solar generation and load demand data. The time dependent model is expected to have more accurate results, but the time independent model has lower computation cost.

The time independent stochastic voltage unbalance assessment algorithm will be developed based on Monte Carlo Simulation. The repetitive simulation will assess voltage unbalance at every iteration and voltage unbalance probability dependence on solar generation penetration will be analysed. The battery systems will be added and voltage unbalance mitigation efficacy will be demonstrated. Next, the time dependent algorithm will be presented. In time dependent algorithm one year time span will be simulated repetitively. In order to mitigate the voltage unbalance, home batteries will be added to the models and three different connection strategies will be simulated. Simulation will be run on three different grid models, each representing type of a region of Finland: rural, intermediate and urban. Each grid model has different topology and number of customers on every bus.

The MATLAB code was developed to calculate voltage unbalance and model stochastic Monte Carlo simulation algorithm.

1.3 Thesis structure

In the theory section, the voltage unbalance phenomenon will be described. The reasons of occurrence and importance in low voltage grid will be discussed. The sequence components methodology for calculating the voltage unbalance will be presented and Transfer Impedance concept utilisation will be justified. The voltage unbalance and Transfer Impedance in other research works will be highlighted.

In the method section, the approach for calculating the voltage unbalance will be presented. The battery connection strategies will be described and modelling aspects will be discussed. After that, facts about the relevance of the stochastic approach will be brought up. Finally, the Monte Carlo Simulation algorithm flowcharts will be shown and commented.

In the result section, the results of time independent and time dependent models will be presented and commented on the goals of the thesis. In the end, some aspects that could be added in future work will be discussed.

2 Theory

2.1 Voltage Unbalance

The three-phase electrical system ideally is meant to work in symmetrical condition. However, real life is much more complicated and many unpredictable circumstances influence voltage waveform. On the high voltage transmission level, the voltage waveform is usually close to symmetry, but electrical system is hardly ever symmetrical on low voltage grid level.

In a symmetrical electrical system the phase voltages are having equal amplitude and angles between the phasors are equal. The sum of such voltages at every instance is equal to zero. The voltage unbalance is a phenomenon in a polyphase electrical system, such as three-phase distribution grid, when phase voltages and phase angles are not equal. The voltage unbalance is illustrated on Figure 1. The red sinusoidal causes the voltage unbalance, because it is having higher amplitude and does not have 120° phase shift between other two phases.

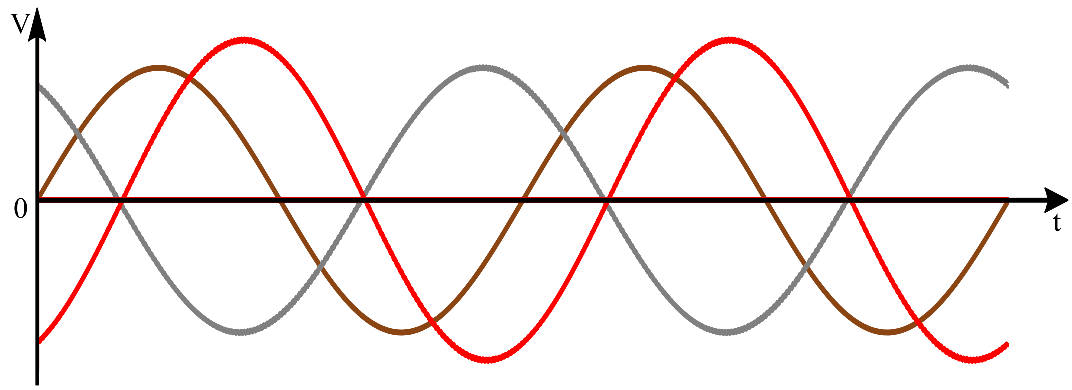

Figure 1: Unbalanced three-phase sinusoidal

2.1.1 Reasons of occurrence

There are several reasons of occurrence for voltage unbalance in low-voltage grid. A major cause for voltage unbalance is non-symmetrical loads. It is common in residential grids to split the phases between buildings or assign a dedicated phase for high power load e.g. water boiler, which works occasionally. Severe voltage unbalance distortions are a result of lighting loads and electrical transportation in urban areas due to its high power demand [8]. In addition to that, an emerging problem is a single-phase charging of electric vehicles [9].

In addition to the non-symmetrical loads, the voltage unbalance sources can be found on transmission and distribution grid level as well. Transformer winding's asymmetrical impedance, open wye and delta transformer banks, blown up fuses on three-phase capacitor banks leads to the voltage unbalance. Additionally, asymmetrical transmission impedance caused by incomplete transposition of transmission lines supplements the list of reasons of the voltage unbalance [8].

Power generation can cause voltage unbalance as well. Non-symmetrical generation have a direct impact on voltage unbalance levels by increasing the voltage in connected phase. One of the types of non-symmetrical generation - the single-phase solar power - is considered in this thesis. It is widely present in low voltage residential grids and even more consumers are expected to install solar arrays. Among the other types of the distributed single-phase generators are wind power and liquid fuel generators.

2.1.2 Relevance

Voltage unbalance is one of the power quality properties, that is set down in European Standard EN 50160. Electricity supplier - distribution system operator - has a responsibility to provide electrical energy with all quality requirements met. The voltage unbalance limit should not be exceeded on customer connection point - point of common coupling. The limit is 2% of the voltage unbalance, during 95% of the 10 minute mean rms values of each period of one week [10]. However, the limit can be locally more strict at locations with high single-phase loads e.g. at electric transport connection points [11]. At these kind of connection points, the background voltage unbalance is limited in order to keep voltage unbalance level under two percent at occasional high single-phase load.

The unbalanced voltage levels can cause problems in grid operation. Most ordinary problem that lies on the surface is increased losses. It is highly recommended to reconfigure grid considering voltage unbalance in order to diminish system losses [12]. Another problem that arises in a grid with the voltage unbalance is the higher utilisation factor of grid components. It increases the wear of grid components and yields to additional grid reinforcement costs for distribution system operators and higher running cost on long term [13].

Induction machines are vulnerable to the voltage unbalance. They are widely used in many applications, which makes the subject of concern. Continuous voltage unbalance at induction motor terminals can permanently damage machine. Since the negative sequence impedance of induction machine is lower than positive sequence impedance, the current unbalance value can be up to ten times higher of the voltage unbalance. Current unbalance can cause high temperature levels in windings and develop reversed torque [14, 15].

Above named problems make voltage unbalance an important power quality aspect, which should be taken into account in grid planning stage.

2.1.3 Sequence Components

In a three-phase electrical system, the voltage unbalance can be quantified by symmetrical components, also known as Fortescue components. It is a powerful method to analyse unsymmetrical phenomena. The three voltage phasors are being split into three components: positive ($v^{(1)}$), negative ($v^{(2)}$) and zero sequence component ($v^{(0)}$). It must be noted, that only the modern meters are capable of measuring symmetrical components, because it requires mathematical operations.

They can be calculated using matrix transformations of the three-phase voltage phasors, as shown in Equation 1 [16]. The rotation operator is given by $a = 1 \cdot \angle 120°$. The current phasors can be transformed to sequence components by applying the same formula as well.

$$\begin{bmatrix} v^{(0)} \\ v^{(1)} \\ v^{(2)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

The voltage unbalance (VU) can be calculated using symmetrical components and it is defined as a ratio of the negative sequence component and the positive sequence component, as shown in Equation 2 [10]. In this thesis, the positive sequence component - $v^{(1)}$ - will be assumed to be equal to rated voltage.

$$VU = \frac{v^{(2)}}{v^{(1)}} \tag{2}$$

2.1.4 Voltage Unbalance in other research

The voltage unbalance related scientific research was done for couple of decades by now and papers related to voltage unbalance caused by distributed solar generation in last ten years. Many of them discuss various aspects of the voltage unbalance caused by single-phase solar generation.

In [17] authors have developed a methodology for voltage unbalance calculation and analysis based on sequence components. Adopting sequence network based methodology allows to split voltage phasors to sequence components and analyse voltage unbalance propagation in different scenarios. Scenarios include changes in line impedances, load demand and grid topology. The result of the research revealed, that variation in line impedance will have higher impact on the voltage unbalance, while load demand change and topology change will have smaller impact. The method developed is elegant. However, the author of the thesis prefer Transfer Impedance method due to it's versatility.

In [18] the sensitivity analysis of voltage unbalance caused by single-phase solar generation was conducted. Analysis is based on the power and location of solar generation in a residential low voltage distribution grid. It was shown, that solar generation installed on an end of a feeder will cause high voltage unbalance in the end and low voltage unbalance in the beginning of a feeder. Furthermore it was shown, that the voltage unbalance can be decreased by solar generation in case of existing background voltage unbalance. Small power of solar generation will compensate background voltage unbalance, however high power solar generation will cause voltage unbalance nevertheless. Background voltage unbalance is usually caused by non-symmetrical load and single-phase solar generation can cover that load, reducing the current flow and the voltage unbalance at point of connection. The analysis was conducted in Monte Carlo Simulation based model with randomised power of a single solar array and fixed quantity of arrays. As opposed to this research, in this thesis the power of a solar array will be fixed and quantity will be randomised.

2.2 Transfer Impedance

There are several ways how to approach to voltage unbalance calculation. The method used in this thesis is based on transfer impedance matrix. Transfer impedance method is rather old fashioned method, because it is straightforward and works well in radial grids. It requires low computational power and thus it was popular in the twentieth century. However, it lacks the agility in calculating complicated grid topologies with looped branches. It suits well the need of calculating the voltage unbalance, because only the negative sequence voltage is going to be calculated and load currents will be neglected due to their symmetry.

2.2.1 Formation of Transfer Impedance

Transfer impedance is a grid impedance model, which consists of n-by-n square matrix of impedances, where n is a number of busses in the considered grid [16]. In other words, transfer impedance matrix is a matrix of mutual impedances between all busses. The impedance elements on the principal diagonal are called driving-point impedance of the busses and they represent an impedance between the slack bus and considered bus. The off-diagonal elements are called transfer impedances of the busses and they represent the impedance by the point of common coupling between two busses in the grid.

Transfer impedance must be calculated for every considered grid separately. A MATLAB code was developed to calculate the transfer impedance according to the grid topology and it is based on the algorithm described in Table 1.

Table 1: Transfer Impedance Calculation [19]

1	Connect solar generation and/or home battery at bus m.
2	Calculate negative sequence current $i_m^{(2)}$ at bus m.
3	Calculate negative sequence voltage $v_n^{(2)}$ at bus n.
4	Find a ratio of voltage at bus n and current at bus m, which will be a nm element of transfer impedance matrix Z_{nm}.
5	Repeat steps 3 and 4 for all busses.
6	Repeat steps 1 to 5 for all busses.

The negative sequence voltage columns vector is going to be calculated by multiplying transfer impedance square matrix by column vector of injected negative sequence currents at every bus, as shown in Equation 3.

$$\underline{v}_n^{(2)} = \underline{Z}_{nm} \cdot \underline{i}_m^{(2)} \tag{3}$$

$$\begin{bmatrix} v_1^{(2)} \\ v_2^{(2)} \\ \vdots \\ v_n^{(2)} \end{bmatrix} = \begin{bmatrix} Z_{1,1} & Z_{1,2} & \dots & Z_{1,n} \\ Z_{2,1} & Z_{2,2} & \dots & Z_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n,1} & Z_{n,2} & \dots & Z_{n,n} \end{bmatrix} \cdot \begin{bmatrix} i_1^{(2)} \\ i_2^{(2)} \\ \vdots \\ i_n^{(2)} \end{bmatrix}$$

Negative sequence current can be obtained in similar manner as shown in Equation 1. If the solar array is connected to a single phase, then negative sequence current can be found simply by dividing phase current by three. If several solar arrays and batteries of one node are connected to different phases, then complex calculations are required, as shown in Equation 1.

In sake of simplicity, it is assumed that all the generators and loads in the model are constant current models. It is also assumed, that proportion of rotating loads is negligible and negative sequence impedance is equal to positive sequence impedance. This was done in order to simplify impedance model and no modifications with impedance values were made [20].

2.2.2 Transfer Impedance in other research

The transfer impedance concept was mostly popular in nineties, but lately in 2016 it was used to calculate voltage unbalance in stochastic assessment model by team of researchers from Germany and Sweden [19]. The voltage unbalance calculation and stochastic framework were adopted as a base for the current thesis.

In [19], transfer impedance was used to calculate negative sequence voltage. The research work considered three different grids ranging from 6-customers to 40-customers grid. Voltage unbalance was calculated multiple times in stochastic framework and then results were compared to deterministic calculation. Changes in solar generation penetration, single solar array power and background voltage unbalance were analysed. Results showed, that at the same solar penetration level, the voltage unbalance can be different: high number of small solar arrays results in lower voltage unbalance, compared to smaller number of high power solar arrays. Additionally, paper discusses about impact on voltage unbalance caused by solar panel tilt angle, connection of three-phase induction motors and electric vehicle chargers. These aspects might be used in continuation of the work.

Authors of [21] have utilised transfer impedance matrix concept in power flow calculations. The method allowed to obtain bus voltages in just several iterations, which lowered the computation cost. In addition, it was possible to model constraints, such as keeping generator's voltage within given limits. Model tolerated changes in considered system's transmission, load and generation parameters. Paper covered the different bus type models, such as transformer bus, generator bus and load bus. Research was done in 1963 and the program code was ran on IBM 704 computer, which gives an idea of the computation cost of the method based on Transfer Impedance.

In [22] the new method was developed to build transfer impedance, also called as bus impedance matrix. The proposed algorithm showed good performance and was fast to recalculate the matrix in case any changes were made in the grid topology. The advanced transfer impedance matrix algorithms can be adopted in future research.

3 Method

3.1 Voltage Unbalance mitigation

High penetration of solar generation in low voltage distribution grid can cause severe voltage unbalance levels due to high injection of negative sequence current component [23]. Introducing home battery to the low voltage grid will have an opportunity to mitigate the voltage unbalance. For that, three different home battery phase connection strategies will be analysed in this thesis.

3.1.1 Battery Connection Strategies

Residential households have a three-phase power and usually loads and small embedded generators are distributed unequally between the phases. However, with an intention of mitigating voltage unbalance, phase to which the battery will be connected could be chosen manually. Home battery charging can increase the level of the voltage unbalance similarly to solar generation. On the other hand, voltage unbalance can be reduced by choosing the right phase connection strategy. The aim is to assess what would be the impact of every strategy on voltage unbalance and evaluate which strategy has the best voltage unbalance mitigating efficacy.

- Strategy 1 - Random phase

  The first strategy will choose phase for home battery connection randomly. Solar array and battery are connected to grid without phase coordination, leading to random phases for both.

- Strategy 2 - Same phase as solar array

  In the second strategy, home battery will be connected to the same phase as solar array. Wires have dedicated colour for each phase and thus solar array phase can be tracked down. This strategy has the biggest potential for mitigating voltage unbalance caused by solar generation.

- Strategy 3 - Phase with highest voltage level

  During the third strategy home battery will be connected to a phase which has the highest voltage level. This strategy requires phase voltage measurements and could require coordination with distribution system operator. Idea is to decrease the voltage level in one phase and mitigate the voltage unbalance.

The strategies 1 and 2 are quite simple in implementation. In strategy 1, the random number generator will be used to determine the phase of solar array and a battery. In strategy 2, the solar array phase will be randomly generated and stored in the map. The battery will use same phase connection map and it's current angle will be rotated accordingly. In strategy 3, the phase voltage calculation precedes the battery connection. The phase voltages at a bus are calculated and the highest one is being stored. Then, the battery is being connected to the same phase. Once that is done, the highest phase voltage is found again. The batteries are connected one at a time and the highest voltage level is evaluated after every battery is connected.

3.1.2 Battery Connection Strategies in other research

The voltage unbalance mitigation by home batteries is relatively young research topic. Affordable home battery systems emerged to market in last decade and since then the research in utilising the potential of home batteries in electrical energy quality have started.

Voltage unbalance mitigation in low voltage grids is definitely important part of a modern electrical grid - the Smart Grid. Home batteries will be an active grid element, which will participate in demand response and power quality regulation. To date, there are not much of research done on that topic. However, electric vehicle charger impact on distribution grid is popular research field at this point. Home batteries are quite similar to electric vehicle chargers, but some differences are still present e.g. availability.

In [24], the voltage unbalance mitigation possibilities in low voltage distribution grid with solar generation were analysed. The energy storage device was connected to the experimental grid and a control algorithm was tested. The analysis was carried out on experimental Small Scale Energy Zone set of devices, which emulated different utility grid parts, like solar array and battery system. The key idea of control strategy was to measure the zero sequence component, hence evaluating the current flow in neutral line. It was then used as a trigger for the battery system to inject power to the grid. Results showed, that single-phase solar generation can reduce voltage unbalance in case of unbalanced load. Next, it was demonstrated that having battery in same phase with solar array will reduce voltage unbalance levels and having them in different phases - will increase the voltage unbalance.

Author of the thesis admires having an emulation system, which is a good way to carry out and validate the voltage unbalance mitigation method. On the other hand, the test is deterministic and is hardly useful in assessing probabilistic voltage unbalance levels for distributed system operators in grid planning stage.

The same team continued their research and in [25] they augmented the system with intelligent active-management algorithm. The single-phase connected home battery output current was modified according to reference phase voltage. The voltage unbalance and losses were analysed at different power factor values. It was concluded, that at leading and unity power factor the voltage unbalance can be mitigated most efficiently.

In 2017 the same team proposed a fuzzy-driven algorithm to control a battery system for mitigating the voltage unbalance in a grid with solar generation [26]. A system had a battery connected to each phase, having total of three batteries. The voltages were measured in each phase and the power flow of each battery was controlled to compensate the voltage unbalance.

During writing the thesis, it was concluded, that voltage unbalance mitigation by home battery is far more than just choosing the connection phase. Voltage unbalance mitigation assessment and strategies must be taken to new level. New methods should be adopted in battery power flow control.

3.2 Modelling

Two algorithms will be presented in this thesis: time independent and time dependent. The second one is built on the base of the first one with few modifications. Both models are based on Monte Carlo Simulation method and gives a statistical result. Monte Carlo Simulation is the solution by probabilistic methods of non probabilistic problems [27]. In other words, the voltage unbalance level is deterministic value and can be calculated for each and every combination of inputs. However, due to large number of input combinations, it is more efficient to randomly choose the input values repetitively and analyse the statistical data acquired.

In this section the model will be described. Solar array and home battery models will be discussed as well as the grids that are going to be used in this research. Then, a short justification and relevance of the method will be discussed. Finally, both algorithms will be described.

3.2.1 Solar Array and Home Battery

Both solar array and home battery are going to be modelled as a constant current model. Constant current models are necessary to simplify the model and provide faster calculation time. In the future, the power producers and loads could be substituted by a more comprehensive models. Both solar arrays and batteries are assumed to work on full load all the time to grant the worst possible case.

The solar array is going to have a power value which corresponds to single-phase 16 ampere circuit - $16\ \text{A} \cdot 230.94\ \text{V} = 3695.04\ \text{W}$. This value was chosen as a highest possible current value in a single phase and it is used as a standard size for one phase circuit breaker. This will allow to model the worst possible case of single-phase current. For a time dependent model, the peak of the solar time series power curve is scaled to match the same value of 16 A circuit.

The home battery model will be based on Tesla Powerwall 2. It is Tesla's second generation home battery system with robust environmental specifications and relatively low lifetime cost [28]. Tesla is a well known brand, which makes the Tesla Powerwall 2 a desirable option in home battery purchase. The charging power of the battery will be assumed to be 5 kW and efficiency as per [29]. In order to find the highest magnitude of the voltage unbalance mitigation at every time instance, the battery capacity will be neglected.

3.2.2 The source data

The data used for the voltage unbalance assessment is based on solar power generation and household energy consumption. Solar array power generation is a simulated data array. The simulation is based on the approach presented in [30]. The generation pattern follows the theoretical maximum solar generation and it does not take into account clouds or any other weather conditions hindering solar irradiance. The location of the solar array is assumed to be Helsinki area in Finland, panels oriented to south at tilt angle of 45°.

Such a set of parameters allows to assess the worst possible voltage unbalance at any time instance along the year. The solar generation data array is scaled such, that the highest peak value is equal to maximum solar generation power of 3695.04 W. The length of data array is one year on a one hour base.

The load consumption data is presented in three arrays. Each array represents household with different heating type: storage heating, district heating and direct electric heating. Consumption data is based on real metering data from Finnish households and represents the typical Finnish household lifestyle. The measured data works well together with typical Finnish grid topologies. The time span is one year on a one hour base, starting at the 1st of July 2008 and end time is the 30th of June 2009.

The source data can be seen in Appendix A. The data shown in the plots is edited in order to be easily readable. The peak power, lowest peak power and mean power were found for every day and plotted in Figure A1.

3.2.3 Grid topologies

Three different grids will be analysed in this thesis. They represent three grid types - predominantly rural (PR), intermediate (IM) and predominantly urban (PU) - and they are based on NUTS region classification. Grids are adopted from research work [31] and the results will be compared with the same work.

Three topologies are having different parameters, such as transformer impedance, cable run impedance and customers per bus. Differences are coming from the nature of the grids: a rural grid has smaller transformer as the load density is small and feeder impedance is bigger as distance between costumers is longer. An urban grid has higher customer density, meaning that the feeding transformer is bigger and cables are thicker. Grid parameters are same as in [31] and are shown in Table 2. Note, that all feeders are assumed to be underground cables and transformer resistance is negligible.

Table 2: Grid Parameters [31]

Region	Transformer Impedance Z_{XFMR}[mΩ]	Feeder Impedance Z_{FEED}[mΩ]	Customers per Bus
PR	j128.0	79.5 + j12.7	1
IN	j40.0	20.0 + j8.2	4
PU	j9.6	10.0 + j4.1	60

The main difference between the grids is the residential house heating type. Heating types presented in this thesis are: storage heating (SH), district heating (DH) and direct electric heating (DEH). Some of the heating types are more frequently present in a region, e.g. predominantly urban region has a share of district heated houses of 95.3%. The rural and intermediate regions have fairly similar heating ratios with approximately half of the houses are connected to utility heating and the rest uses storage and direct electric heating.

The heating type ratios are same as in [31] and can be seen in Table 3

Table 3: Heating types per region [31]

Region	SH [%]	DH [%]	DEH [%]
PR	5.9	52.9	41.2
IN	7.6	52.5	39.9
PU	0.4	95.3	4.2

The rural grid topology is shown on Figure 2. Grid has 8 customer busses, one customer on each. Since bus can allocate only one customer, the maximum number of solar arrays and batteries per bus is limited to one. The bus without an index is not considered as a customer bus and no customers, solar arrays, nor batteries will be connected to it.

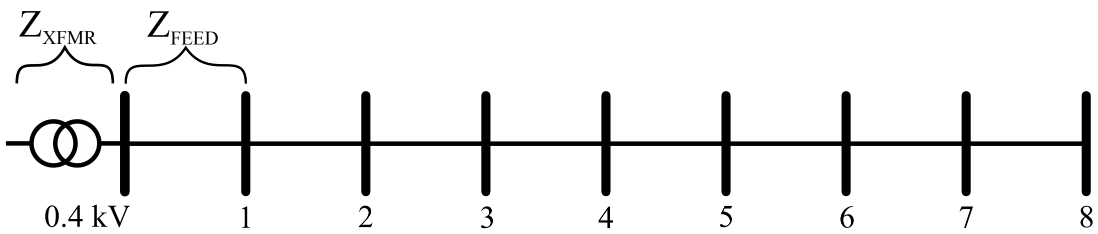

Figure 2: Rural grid (PR) topology [31]

The transformer impedance - Z_{XFMR} - can be found in Table 2 as well as feeder impedance Z_{FEED}. Note, all feeders are assumed to have same length and that feeder impedance Z_{FEED} is between two busses only. That means e.g. impedance between transformer and bus nr. 2 will be twice of that.

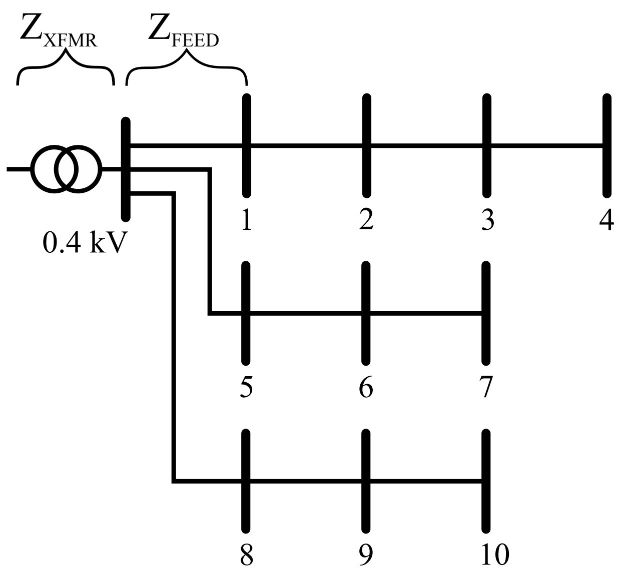

Figure 3: Intermediate grid (IN) topology [31]

The intermediate grid is presented on Figure 3. It has total of 10 customer busses and four customers on each bus. This sums up to 40 total customers in the grid, each can have a solar array and a home battery installed.

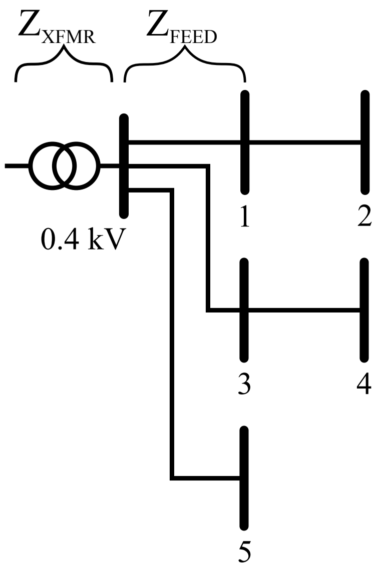

Figure 4: Urban grid (PU) topology [31]

Figure 4 shows the urban grid topology, which has five busses and 60 customers per bus. Total number of customers is hence equal to 300.

The voltage unbalance will be assessed only on customer busses i.e. on the busses with numerical indexes.

3.2.4 Relevance of stochastic approach

In this section, the relevance of stochastic approach and Monte Carlo Simulation will be discussed. Arguments will be presented on why it was chosen instead of deterministic calculation methods and why is it suitable for this kind of problem solution.

Monte Carlo Simulations are having the priority over deterministic models because of lower computation costs. In many-dimensional applications, it is faster to randomly choose variable values and calculate the output, while in deterministic models all possible combinations of input variables should be calculated [27]. The considered model has several variables, such as solar array quantity, location and phase connection. The battery modelling requires as much variables as solar array modelling. In time dependent model, the time dimension adds up to the list of variables and makes the total number of possible combinations unbearable for computation devices.

Monte Carlo-based models allows to simulate probability distributions of input variables. Some inputs, such as solar irradiance or wind, are practically impossible to predict. In this case, probability distributions are handy, which allows to estimate the probability of occurrence of an input value. In the current thesis, solar generation will be given as an input array and in future works it can be replaced by probability distribution of solar array generation power. Additionally, probability distribution could be used in such variables as battery state-of-charge, load power demand and electric vehicle charging power. Probability distribution is useful in models with distributed renewable energy generation due to it's stochastic nature and bi-directional power flow.

Finally, Monte Carlo Simulation results provide more possibilities in result analysis. Since the results are an array of values of different modelled scenarios, the one can interpret them in many ways. Statistical methods are applicable in this case and mean values as well as standard deviations can be found. Results can be presented in many different ways using tables, probability distribution functions, histograms etc. In this thesis, the most important output value is considered to be 95$^{\text{th}}$ percentile value. All the values, that are higher than 95$^{\text{th}}$ percentile value, are considered unlikely to happen. Probability of occurrence of 5% is sufficiently small to be neglected and there is no need to consider worst case scenario in grid planning [23]. It is unlikely to happen in a grid that all the solar arrays and batteries will be connected to one phase only. However, it is up to distribution system operator to decide how big risk it is willing to take. The 90$^{\text{th}}$ percentile value has lower safety margin, but is less demanding. This thesis will consider the 95$^{\text{th}}$ percentile and mean values as output of the model.

3.3 Monte Carlo Simulation Algorithms

Thesis will consider two algorithms for voltage unbalance assessment. One is time independent algorithm and it does not use a time as a variable. In other words - the model is static. The second is time dependent algorithm and it does have a time as a variable. The time increment is one hour and it cycles through a one year time span with increment of one hour. At every hour, the solar power curve and load demand are read and used in voltage unbalance calculation.

The two modelling approaches will be compared. The time independent algorithm has significantly lower computation time compared to time dependent algorithm. However, the time dependent algorithm is expected to have better representation of lifestyle dependency and seasonal voltage unbalance variations. The results will be compared and evaluated by criteria: closeness to reality and computation time.

3.3.1 Time Independent algorithm

The flowchart of the time independent algorithm is shown on Figure 5. The model can be divided into two parts. In the beginning of the first part, the model reads the strategy - variable which defines the way how the battery will be connected - and then variables being initialised, including iteration and solar array quantity.

Then, the solar array is being modelled. The random locations of solar arrays is being generated and random connection phase is being given to each of the solar arrays. Locations of solar arrays is being kept within busses with numerical indexes i.e. customer busses. In case of intermediate and urban grids, several solar arrays can be connected to one bus.

In the second part of the algorithm, the battery is being modelled. Random numbers of batteries is being generated, keeping the number smaller than or equal to the number of solar arrays. Then, random locations of batteries are being generated. Locations are sampled from the location of solar arrays. It is assumed, that only the solar array owners can have home batteries installed. For example, if the random number generator will choose just one solar array for the entire grid, then the battery will be connected to very same customer node as the solar array. Finally, the battery connection phase is being generated according to the chosen strategy. If the strategy is equal to zero, then no batteries will be modelled and only solar array impact on voltage unbalance will be analysed.

After the battery is modelled, the voltage unbalance is being calculated. Voltage unbalance is calculated at every iteration and value is stored. Model cycles 1000 iterations for each possible number of solar arrays and then data array is being analysed.

Note, that on Figure 5, some of the words are being replaced with abbreviations in sake of efficient space usage in the flowchart. The abbreviations are listed in the appropriate section of the beginning of the thesis.

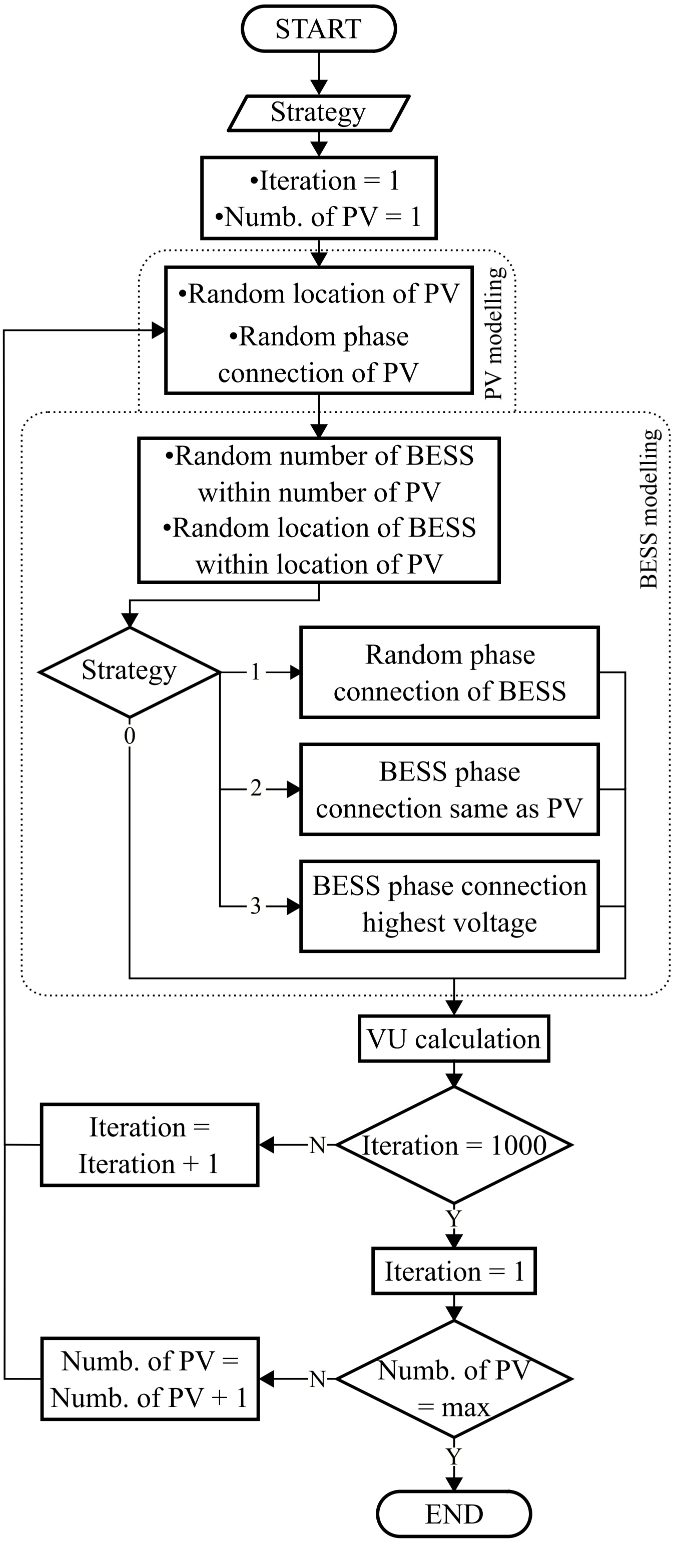

Figure 5: Flowchart of the time independent algorithm

3.3.2 Time dependent algorithm

The time dependent framework is based on time independent model. Several modifications were made to include time series variables. Solar power generation and load demand are an array structure of energy data per each hour during one year.

In the beginning, the user should give the strategy type to be simulated. The strategy will determine the phase connection of battery system, as it was described before. In addition to the strategy, the hosting capacity is given to the model as well. Hosting capacity (HC) is a variable, which determines the number of solar arrays in the grid. It is equal to a ratio of total solar generation maximum value in a grid and total load demand maximum value during a year, as shown in Equation 4.

$$HC = \left. \frac{S_{PV,max}}{S_{demand,max}} \right|_{year} \tag{4}$$

Due to the probabilistic load model, the hosting capacity is not a rigid number. Every time the grid is being modelled, the loads are assigned to each node with probability of occurrence of that load type in a region. This leads to a different number of solar arrays at every iteration. The time dependent algorithm will be simulated at three hosting capacity values: 25%, 75% and 125%. The approximate number of solar arrays corresponding to hosting capacity is shown in Table 4.

Note, that whatever the hosting capacity is, it has a rigid limit. The limit is defined by the assumption of maximum single solar array power and by the assumption that a customer can have only one solar array. Values in the brackets shows the number of solar arrays without the limit.

Table 4: Hosting capacity to number of solar arrays

Region	Hosting Capacity	Number of solar arrays
PR	25%	2
	75%	7
	125%	8 (11)
IN	25%	8
	75%	25
	125%	40 (44)
PU	25%	24
	75%	74
	125%	123

The hosting capacity values were inspired by the results presented in [31]. The paper analysed limiting constraints of a grid with distributed solar generation. It was shown, that rural grid at rated voltage can host 128.9% of single-phase solar generation, before the power quality parameters will fall below acceptable levels. The hosting limit in intermediate and urban region were even lower. It was decided to use 125% hosting capacity as a starting point and simulate several cases with lower hosting capacities.

After the Iteration and Hour variables are initialised, the solar array is being modelled. This part has an addition to the previous model - the number of solar arrays is being calculated. Number of solar arrays depends on the given hosting capacity value and the number of arrays is being kept same until the end of the simulation. The battery modelling part has no changes compared to time independent algorithm.

Changes were made in the voltage unbalance calculation part. The model cycles trough every hour in a power curve time series. First, it finds the power output of solar arrays and calculates corresponding negative sequence current. Then, the battery power is being calculated by finding the difference of solar array generation and load demand at every load point. Battery charges at excessive solar power generation and supplies power to the load when solar generation is not enough to cover the demand. The battery operating conditions are illustrated of Figure 6.

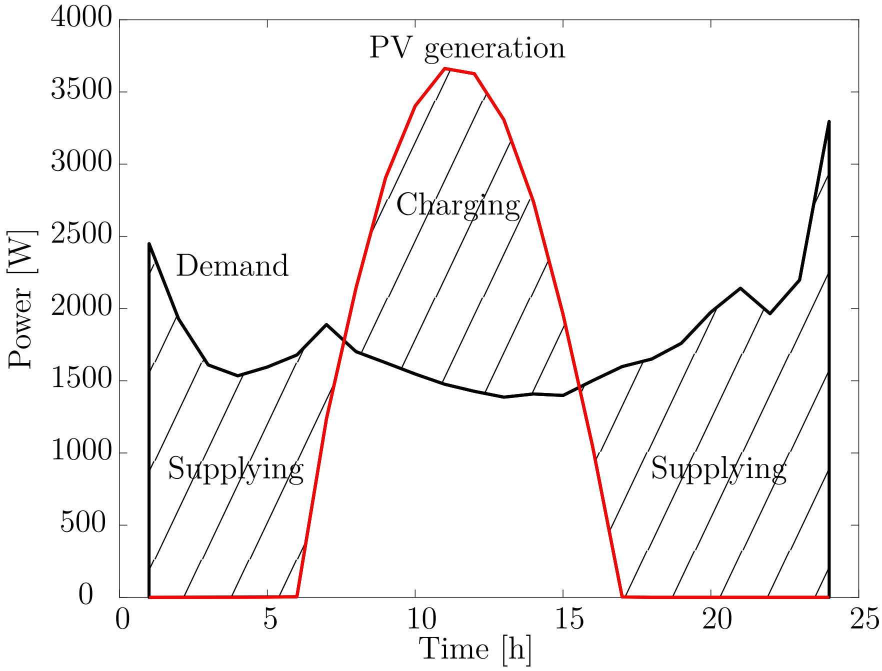

Figure 6: Home battery operating conditions

The power curves presented on Figure 6 are a slice from the year long time series arrays. It depicts a one day load curve from the 1st of April 2009 of a household with direct electric heating and a solar generation curve at the same day. The voltage unbalance at every customer bus is calculated for every hour. After the one year time series ends, the simulation goes on with next iteration and the solar arrays and batteries are randomised and simulated one again. The total number of iterations is equal to 100.

The quantity, location and phase connection is being generated with uniform distribution. In other words, there is equal probability for e.g. that solar array is going to be connected to phase a, b or c. The load type is being chosen according to the weights shown in Table 3. All loads are assumed to be symmetrical and do not cause voltage unbalance.

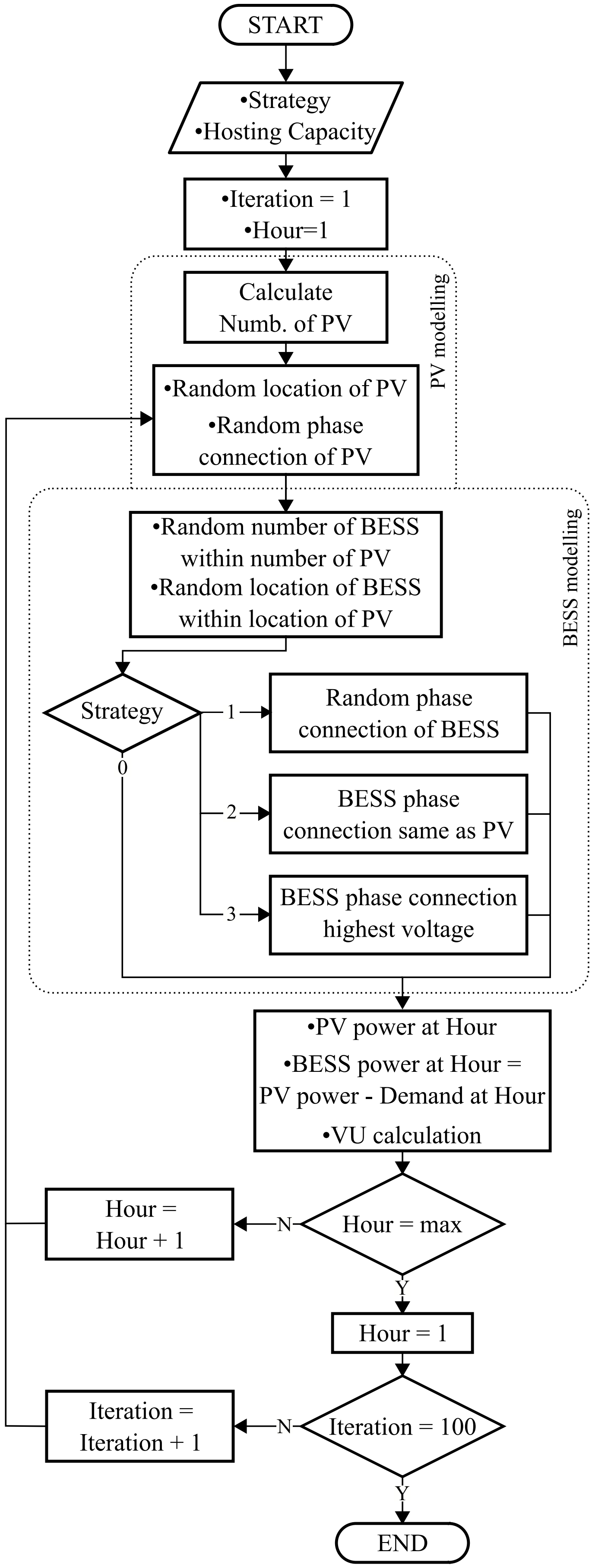

Figure 7: Flowchart of the time dependent algorithm

3.3.3 Monte Carlo Simulation in other research

The stochastic approach for load flow calculations and power quality assessment is popular nowadays. There is no certain framework for every application. Instead, every work is unique and utilises Monte Carlo technique differently. There are not much of research being done in voltage unbalance caused by single-phase solar generation and voltage unbalance mitigation by home batteries. However, some works, that supported writing this thesis, are going to be discussed here.

In [32], the voltage unbalance caused by single-phase solar generation was assessed by stochastic method. The results show the maximum size of a solar array as a function of the solar penetration level. The input for the algorithm is solar array power and solar penetration level. Then, similarly to this thesis, the location and connection phase were selected randomly, with uniform distribution. The voltage unbalance is calculated 3000 times for each node on the 10-minute basis. Calculating voltage unbalance on 10-minute basis is a good practice, because it matches the voltage unbalance limit definition [10]. On the other hand, it would require meter to take measurements with same time increment. Such a fast measurements would generate huge amount of data. Finally, the week with highest voltage unbalance levels was presented. The algorithm utilises probabilistic solar generation and load patterns. Probabilistic patterns provide faster calculation time, but still they are synthetic and do not take into account special events related to lifestyle of people.

A research team from Curtin University, Perth, Australia, is working on power quality problems in Smart Grids. In [33], the voltage regulation methods were proposed and stochastic framework was developed for a residential distribution grid with single-phase solar generation. Phase voltages were regulated to mitigate the voltage unbalance, while keeping phase voltages within standard limits. Three voltage regulation techniques were presented: on load tap changer (OLTC), solar array reactive power control and solar array active power control. In this thesis, the voltage mitigation is done by active power control with a home battery. Nevertheless, the other two voltage control techniques are worth trying in later research. The stochastic framework developed was assessing phase voltages during 24 hours. The solar generation and loads are also probabilistic as in previous work mentioned. However, the author of the thesis finds, that load and solar generation patterns could be generated at every iteration, instead of once, in the beginning of the simulation. That way, the results would represent real life more accurately.

Author of the thesis would like to point the [19] one more time. The stochastic voltage unbalance assessment algorithm developed was applied to two distribution grids in Sweden. The grids have solar arrays with same power installed, but the size of the grid is different. One grid has 28 customers, while another one just 6. Author of the thesis would like to interpret this as a grids of different regions and point out the voltage unbalance trends depending on grid size. At the same solar penetration levels, the voltage unbalance is lower in the bigger, 28-customer grid. It can be concluded, that grids with lower customer density can have higher voltage unbalance levels.

4 Results

In this section, the results will be presented. The voltage unbalance values calculated by two models will be presented and discussed. Voltage unbalance dependency on number of solar arrays connected to a grid will be analysed and regional differences of the voltage unbalance will be shown. Battery connection strategy impact on the voltage unbalance levels will be estimated.

4.1 Results of Time Independent modelling

The results of time independent modelling consist of three plots, each demonstrating voltage unbalance in different region. Since time independent model can not show voltage unbalance levels along a year or any other time span, the voltage unbalance will be plotted against number of solar arrays. Each plot have four subplots describing different battery connection strategies applied. Reminding the reader, that strategy 0 stands for solar generation only, strategy 1 - random phase for battery, strategy 2 - same phase for solar array and battery and strategy 3 - battery to phase with highest voltage.

The quantities shown on the plots are marked as follows. The $VU_{\text{exp, mean}}$ denotes the mean value of the voltage unbalance that is being expected to occur in the grid. It is calculated over all the customer busses. The $VU_{95\%,\text{ mean}}$ denotes the mean value of the 95^{th} percentile of the voltage unbalance. It is being calculated over all busses as well. The $VU_{95\%,\text{ max}}$ denotes the maximum value of the 95^{th} percentile. Unlike the $VU_{95\%,\text{ mean}}$, the $VU_{95\%,\text{ max}}$ shows the maximum voltage unbalance value of a single bus.

4.1.1 The Predominantly rural region

The results of the rural region are shown on Figure 8. In the solar only case, the voltage unbalance exceeds the 2% limit at 8 solar arrays. However, the 95^{th} percentile value exceeds the limit at three solar arrays and on a single bus, the limit can be exceeded already at two solar arrays.

In case of battery being connected as per strategy 1, the voltage unbalance is raised significantly. The mean value is within the limits up until four solar arrays. But 95^{th} percentile value is always above 2%. The maximum 95^{th} percentile voltage unbalance that can be gained on a single bus is around 7.5%.

Strategy 2 - connecting battery and solar array to same phase - has good voltage unbalance mitigation efficacy. The mean value does not exceed the limit and 95^{th} percentile exceeds it at five solar arrays. Up to two solar arrays is tolerable to be connected to the grid, but connecting the third one can cause voltage unbalance slightly over 2% on a single bus level.

The third strategy is showing good efficacy. The overall voltage unbalance levels are very similar to strategy 2. The 2% limit is exceeded by 95^{th} percentile max value at 3 solar arrays, the 95^{th} percentile exceeds at five and the mean value stays below the limit within all range.

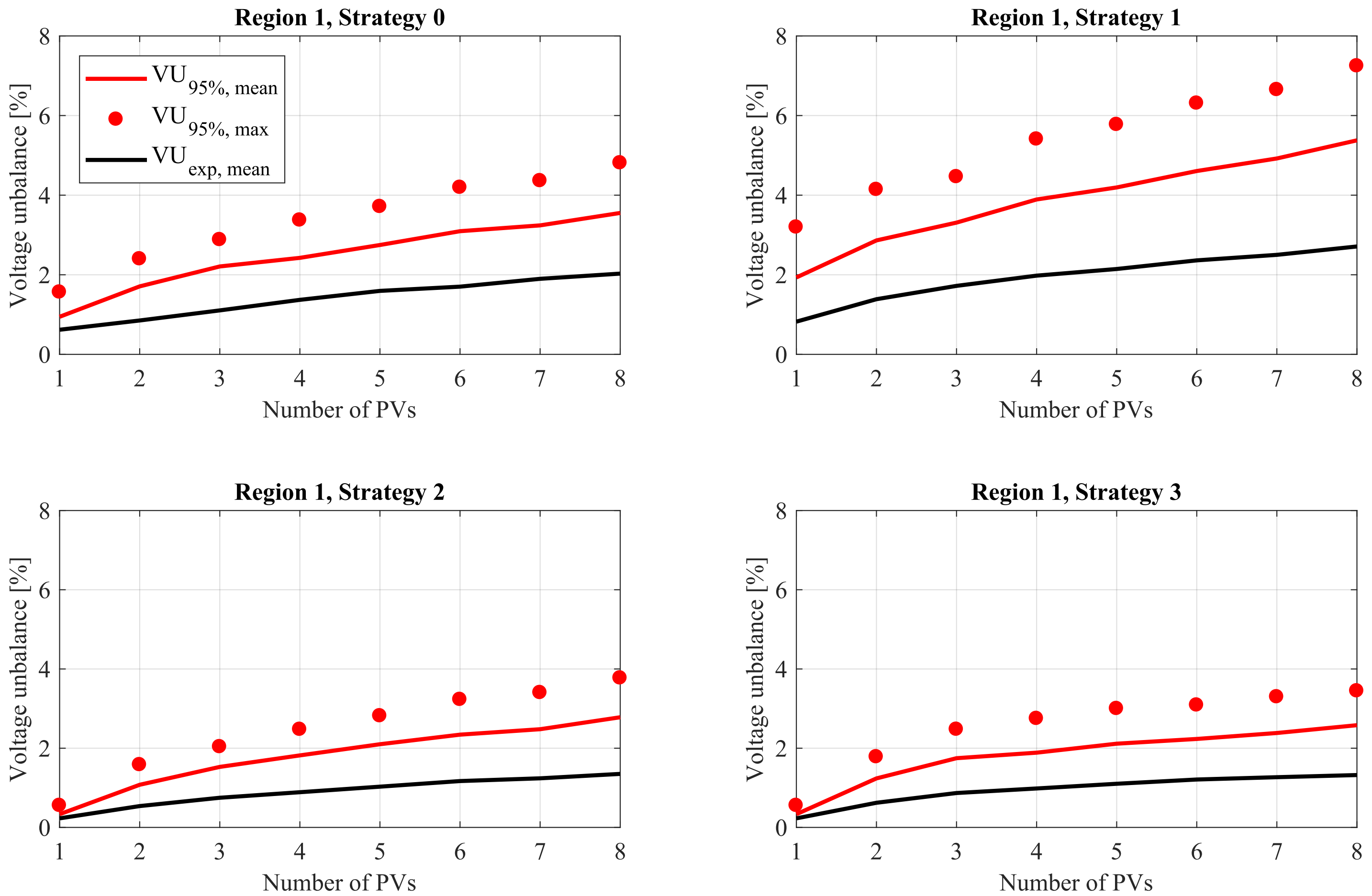

Figure 8: Voltage unbalance dependency of solar array penetration - PR

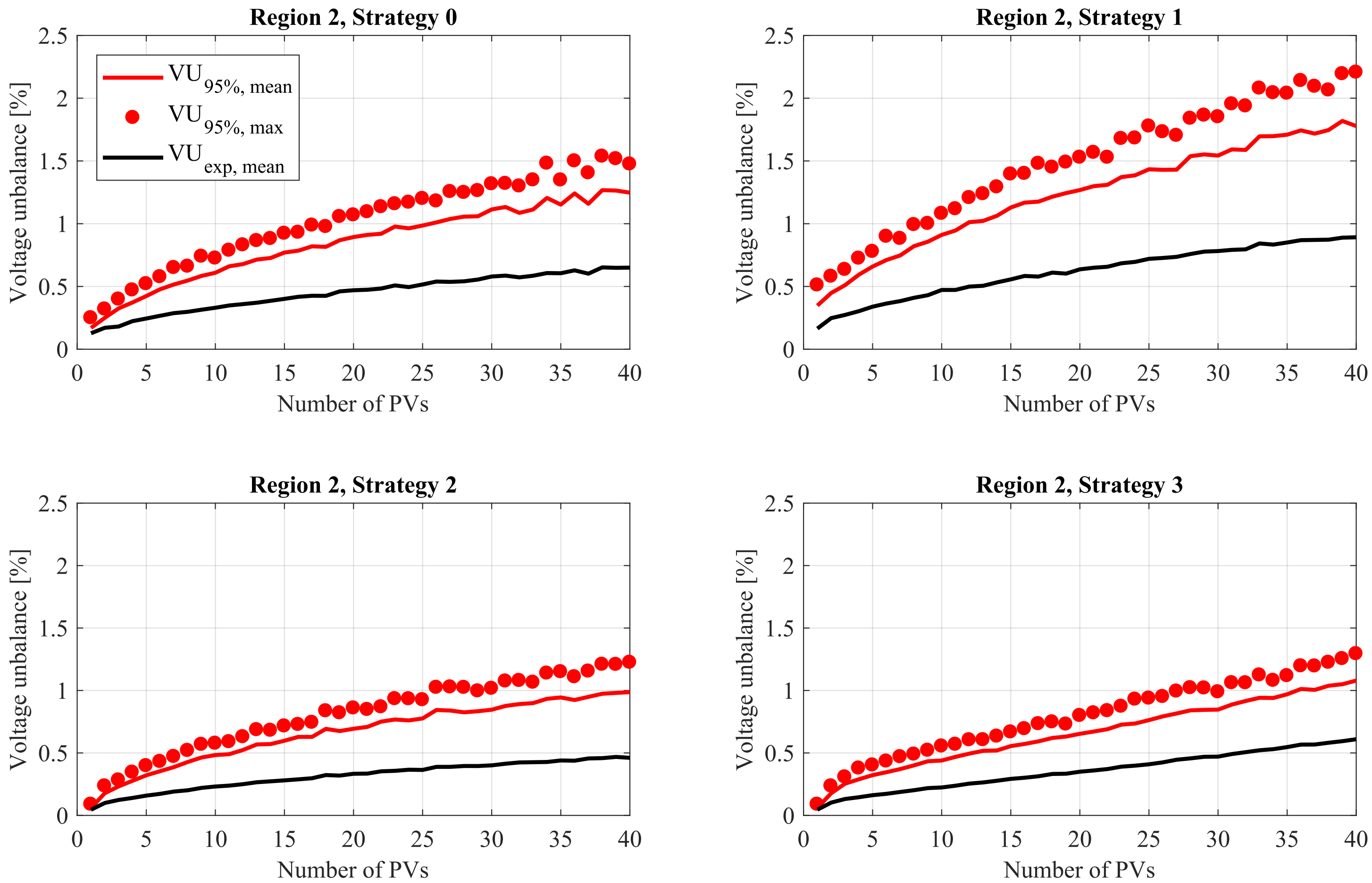

Figure 9: Voltage unbalance dependency of solar array penetration - IN

4.1.2 The Intermediate grid

The results of the intermediate region are shown on Figure 9. In the solar only case, the mean value of the voltage unbalance stays below 1% all the time. The 95th percentile value is below 1.5% of voltage unbalance, but 95th percentile maximum value exceeds 1.5% at very high number of solar arrays.

During the strategy 1, the voltage unbalance has risen. The 95th percentile value now exceeds 1.5% of the voltage unbalance at 30 solar arrays and more. Starting from 33 solar arrays in the grid, the voltage unbalance can exceed the limit of 2% on single bus level with 5% of probability.

Strategy 2 demonstrated good voltage unbalance mitigation effect. The mean and 95th percentile values are kept below 1% of the voltage unbalance. The 95th percentile value exceeds 1% in case of 30 solar arrays and more. Needless to say, that 1% of the voltage unbalance is considered tolerable and cause no issues in grid operation.

The third strategy - connecting battery to the phase with highest voltage level - demonstrates results similar to previous case. In none on the cases, the voltage unbalance reaches the limit. Despite the similar VU levels, the curves of two strategies are having different shapes. By visual inspection, strategy 2 curve has exponential form, while strategy 3 has linear form.

4.1.3 The Predominantly urban grid

The results of the intermediate region are shown on Figure 10. In solar only case, the mean value reaches 0.5% of voltage unbalance and the 95th percentile reaches 1% of voltage unbalance at maximum number of solar arrays. The 95th percentile on a single bus level can exceed 1% of voltage unbalance.

In case of connecting battery to random phase, the voltage unbalance is higher. The mean value exceeds 0.5% and the 95th percentile is close to 1.5%. The 95th percentile maximum value exceeds 1.5% of the voltage unbalance. In any situation, the voltage unbalance does not violate 2% limit.

On this figure, the curves of strategy 2 and 3 has same shapes as on Figure 9. The strategy 2 has exponential curve, the mean value of which is below 0.5% of VU. The 95th percentile values are slightly below 1%. The strategy 3 has linear curve, but it reaches higher VU levels, if compared to strategy 2. The mean value exceeds 1% and 95th percentile values are around 1.75% of VU at maximum number of solar arrays.

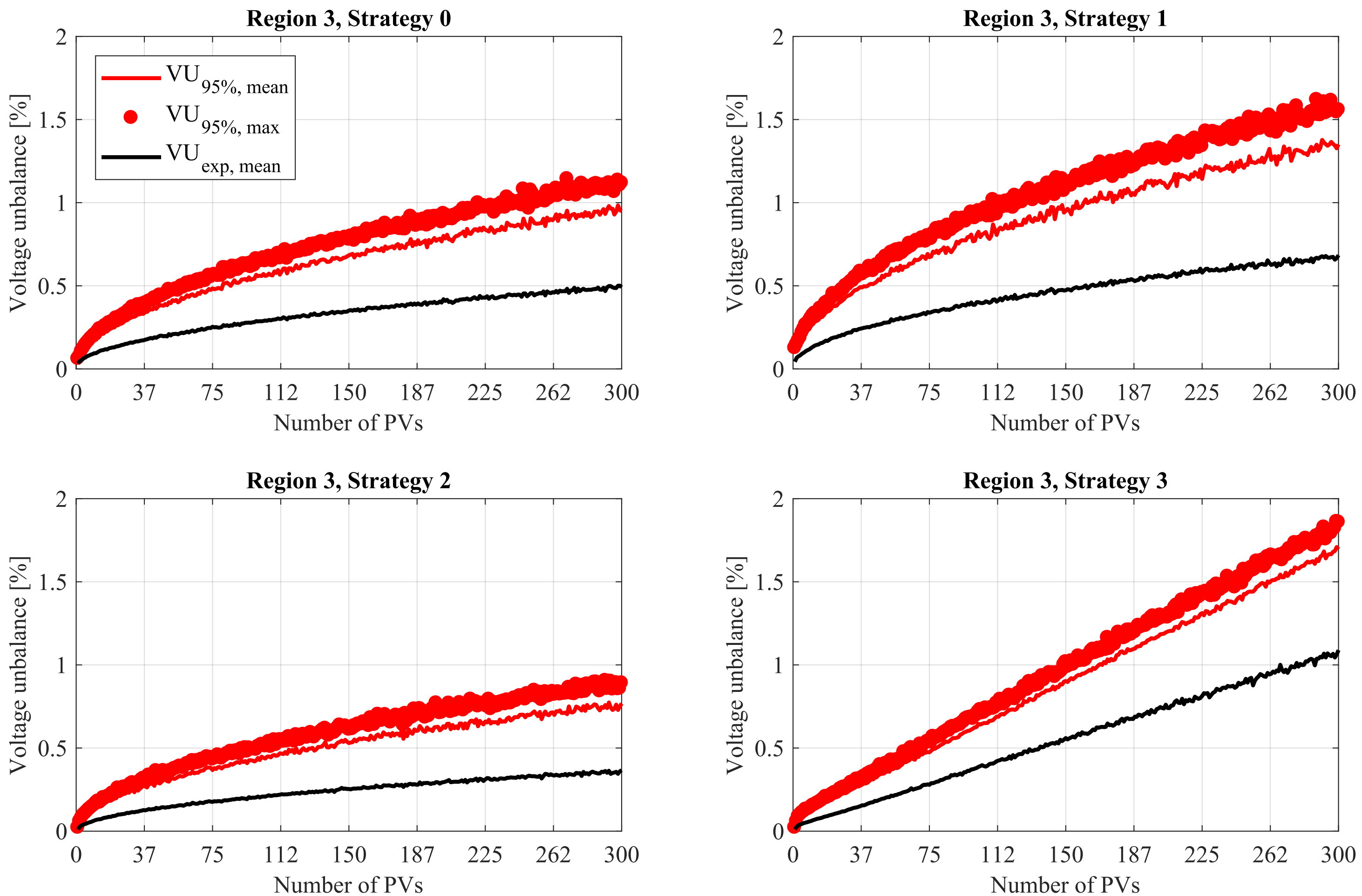

Figure 10: Voltage unbalance dependency of solar array penetration - PU

4.2 Results of Time dependent modelling

In this section, the results of time dependent model will be presented. Results will be divided into three parts. Firstly, voltage unbalance peak values will be presented. Then, the voltage unbalance limit violation count and finally, the probability distribution function of voltage unbalance will be shown.

4.2.1 Voltage Unbalance peak values

Four tables, each presents the results at different battery connection strategy. Results of three regions at three different solar hosting capacities are shown: 25%, 75% and 125%. The maximum values of the voltage unbalance are shown as mean, 95th percentile mean and 95th percentile maximum values per each season of a year.

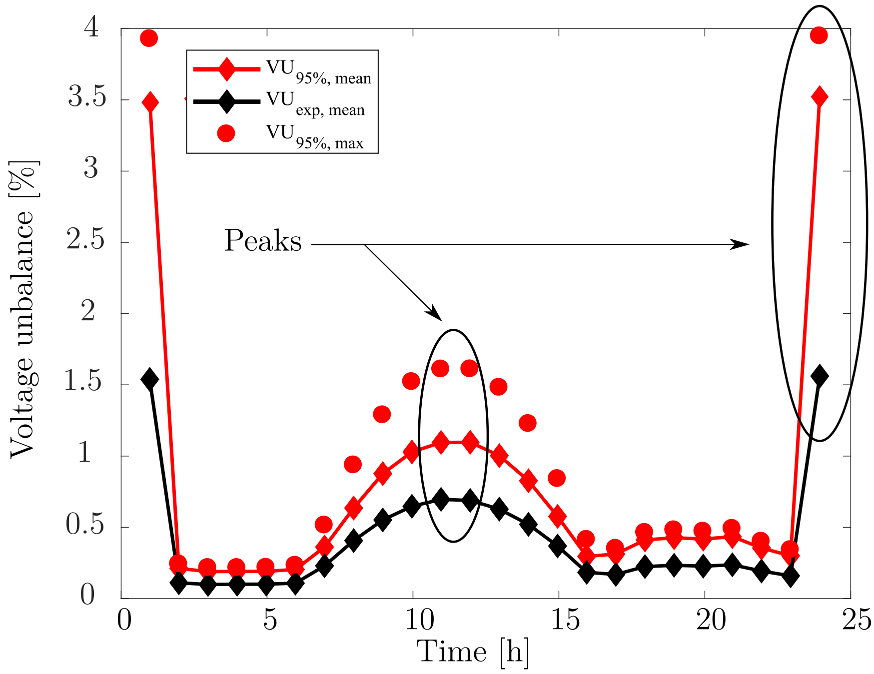

Figure 11: Voltage unbalance peak values

Before proceeding with the tables, a short description should be given about the presented values. The voltage unbalance results are stored as a time series array. The 95th percentile and mean values are shown per each hour along the year. On the Figure 11, the voltage unbalance during the 1st of April 2009 is shown for a household with direct electric heating in region 3 (PU). It corresponds with Figure 6, shown previously. It can be seen, that voltage unbalance changes during the day depending on the solar generation and load demand. The peak values of the voltage unbalance are being measured for every single day and the highest peak value in a season is shown in the forthcoming tables.

In Table 5, the results of strategy 0 are presented. In region 1, at 25% HC, the voltage unbalance on a single bus level reaches 2% limit. At 75% HC, the 95th percentile mean values exceeds the 2% limit. At 125% HC, only the mean voltage unbalance stays below the limit, while the 95th percentile values exceeds it during all the seasons. In region 2, the 95th percentile mean value can reach 1% level and 95th percentile maximum value 1.33% of the voltage unbalance at high HC. In region 3, the voltage unbalance levels are less than 1% in any case.

Table 5: Voltage unbalance peak values at solar arrays only

Strategy 0			VU highest peak value [%]			
	PV HC	VU level	Winter	Spring	Summer	Autumn
Region 1 (PR)	25 %	exp mean	0.69	0.73	0.68	0.67
		95% mean	1.36	1.45	1.38	1.34
		95% max	2.07	2.21	2.10	2.04
	75 %	exp mean	1.37	1.44	1.36	1.32
		95% mean	2.51	2.65	2.51	2.44
		95% max	3.57	3.78	3.57	3.47
	125 %	exp mean	1.50	1.59	1.50	1.47
		95% mean	2.72	2.87	2.72	2.64
		95% max	3.94	4.17	3.94	3.83
Region 2 (IN)	25 %	exp mean	0.24	0.25	0.24	0.23
		95% mean	0.45	0.48	0.45	0.44
		95% max	0.69	0.73	0.69	0.67
	75 %	exp mean	0.44	0.47	0.44	0.43
		95% mean	0.89	0.94	0.89	0.87
		95% max	1.26	1.33	1.26	1.22
	125 %	exp mean	0.52	0.55	0.52	0.51
		95% mean	0.93	0.99	0.93	0.91
		95% max	1.24	1.31	1.24	1.21
Region 3 (PU)	25 %	exp mean	0.10	0.11	0.10	0.10
		95% mean	0.20	0.21	0.20	0.19
		95% max	0.31	0.33	0.31	0.30
	75 %	exp mean	0.19	0.20	0.19	0.18
		95% mean	0.37	0.39	0.37	0.36
		95% max	0.52	0.55	0.52	0.50
	125 %	exp mean	0.24	0.25	0.24	0.23
		95% mean	0.47	0.50	0.47	0.46
		95% max	0.72	0.76	0.72	0.70

In Table 6, the results of strategy 1 are presented. The voltage unbalance levels have risen in all cases. In region 1, the 2% voltage unbalance limit is violated already at 25% HC. At 75% HC the 95th percentile mean value exceeds 2% limit. At 125% HC, the mean value of voltage unbalance gets close to the limit and it can reach up to 4.4%. In region 2, at 25% HC the voltage unbalance does not exceed 1%. At 75% and 125% it does exceed 2%, having the peak at 1.71%. In region 3, the voltage unbalance has increased compared to the previous strategy, but it still stays below 1% level in all cases.

Table 6: Voltage unbalance peak values at battery connection strategy 1

Strategy 1			VU highest peak value [%]			
	PV HC	VU level	Winter	Spring	Summer	Autumn
Region 1 (PR)	25 %	exp mean	0.83	0.90	0.88	0.85
		95% mean	1.48	1.63	1.60	1.53
		95% max	2.19	2.41	2.37	2.28
	75 %	exp mean	1.59	1.71	1.64	1.59
		95% mean	2.82	3.03	2.92	2.82
		95% max	3.91	4.23	4.06	3.92
	125 %	exp mean	1.62	1.76	1.71	1.64
		95% mean	2.76	3.03	3.02	2.85
		95% max	3.91	4.40	4.41	4.11
Region 2 (IN)	25 %	exp mean	0.26	0.28	0.28	0.27
		95% mean	0.53	0.58	0.57	0.55
		95% max	0.78	0.85	0.83	0.80
	75 %	exp mean	0.44	0.48	0.46	0.44
		95% mean	0.83	0.90	0.88	0.85
		95% max	1.10	1.17	1.08	1.07
	125 %	exp mean	0.60	0.65	0.62	0.60
		95% mean	1.10	1.19	1.16	1.12
		95% max	1.56	1.71	1.61	1.56
Region 3 (PU)	25 %	exp mean	0.12	0.13	0.12	0.12
		95% mean	0.24	0.26	0.24	0.24
		95% max	0.35	0.38	0.36	0.35
	75 %	exp mean	0.23	0.24	0.23	0.22
		95% mean	0.42	0.46	0.43	0.42
		95% max	0.63	0.67	0.64	0.62
	125 %	exp mean	0.28	0.30	0.28	0.27
		95% mean	0.51	0.55	0.52	0.50
		95% max	0.78	0.81	0.77	0.75

In Table 7, the results of strategy 2 are presented. In region 1 at 25% HC, the voltage unbalance is lower than 2% limit. At 75% HC, the 95^{th} percentile max value exceeds the limit and, at 125% HC, the 95^{th} percentile mean value approaches it. In region 2, the worst case voltage unbalance slightly exceeds 1.3% level and in region 3 - 0.6% level.

Table 7: Voltage unbalance peak values at battery connection strategy 2

Strategy 2			VU highest peak value [%]			
	PV HC	VU level	Winter	Spring	Summer	Autumn
Region 1 (PR)	25 %	exp mean	0.62	0.56	0.36	0.55
		95% mean	1.25	1.14	0.90	1.13
		95% max	1.72	1.68	1.39	1.68
	75 %	exp mean	0.99	1.00	0.89	0.88
		95% mean	1.90	1.88	1.80	1.76
		95% max	2.69	2.78	2.60	2.56
	125 %	exp mean	1.06	1.00	0.87	0.91
		95% mean	2.27	2.03	1.77	2.00
		95% max	3.18	2.86	2.60	2.82
Region 2 (IN)	25 %	exp mean	0.22	0.21	0.17	0.21
		95% mean	0.43	0.41	0.39	0.41
		95% max	0.58	0.55	0.47	0.54
	75 %	exp mean	0.37	0.34	0.27	0.34
		95% mean	0.81	0.77	0.62	0.76
		95% max	1.08	1.04	0.87	1.03
	125 %	exp mean	0.43	0.40	0.36	0.39
		95% mean	0.93	0.86	0.78	0.85
		95% max	1.32	1.23	1.12	1.22
Region 3 (PU)	25 %	exp mean	0.07	0.07	0.07	0.07
		95% mean	0.17	0.17	0.15	0.17
		95% max	0.27	0.27	0.23	0.27
	75 %	exp mean	0.14	0.14	0.13	0.13
		95% mean	0.34	0.33	0.29	0.33
		95% max	0.50	0.48	0.42	0.48
	125 %	exp mean	0.16	0.17	0.16	0.15
		95% mean	0.46	0.44	0.34	0.44
		95% max	0.69	0.65	0.50	0.65

In Table 8, the results of strategy 3 are presented. In region 1, the 2% limit is not violated only at the 25% HC. At 75% and 125% of HC, the voltage unbalance values can reach very high values - 7.1%. In region 2 at 25% HC, the voltage unbalance is below the limit. At 75% HC, the limit can be exceeded at 95th percentile mean value and, at 125% HC, the limit is exceeded at the mean value. In region 3, the 2% limit can be exceeded by the 95th percentile maximum value at 75% HC.

Table 8: Voltage unbalance peak values at battery connection strategy 3

Strategy 3			VU highest peak value [%]			
	PV HC	VU level	Winter	Spring	Summer	Autumn
Region 1 (PR)	25 %	exp mean	0.69	0.62	0.43	0.62
		95% mean	1.40	1.37	0.85	1.37
		95% max	1.82	1.82	1.24	1.82
	75 %	exp mean	1.80	1.59	0.97	1.56
		95% mean	4.16	3.91	1.89	3.88
		95% max	5.72	5.35	2.69	5.31
	125 %	exp mean	2.11	1.86	1.03	1.83
		95% mean	5.14	4.78	2.11	4.74
		95% max	7.11	6.67	3.00	6.61
Region 2 (IN)	25 %	exp mean	0.52	0.48	0.19	0.47
		95% mean	0.87	0.81	0.35	0.81
		95% max	1.11	1.08	0.51	1.07
	75 %	exp mean	1.46	1.35	0.47	1.34
		95% mean	2.76	2.57	0.92	2.55
		95% max	3.59	3.33	1.20	3.31
	125 %	exp mean	2.26	2.08	0.76	2.06
		95% mean	4.32	4.06	1.47	4.03
		95% max	5.50	5.15	1.83	5.10
Region 3 (PU)	25 %	exp mean	0.27	0.27	0.11	0.27
		95% mean	0.64	0.63	0.21	0.63
		95% max	0.86	0.85	0.34	0.85
	75 %	exp mean	0.74	0.72	0.31	0.72
		95% mean	1.93	1.92	0.55	1.91
		95% max	2.59	2.57	0.93	2.57
	125 %	exp mean	1.32	1.31	0.53	1.30
		95% mean	3.32	3.29	0.87	3.29
		95% max	4.46	4.43	1.42	4.42

4.2.2 Voltage Unbalance limit violation count

The number of weeks violated the voltage unbalance limit are going to be presented in this section. The table is divided into four different strategies and is having three solar generation hosting capacity levels for each. The results are split into seasons of a year.

The voltage unbalance violation is considered as per EN 50160 standard, which was discussed in Section 2.1.2. The standard sets the voltage unbalance measurement increment to 10 minutes, but in case of this research, the load data was given in 1 hour step. The 5% duration of a week is approximately 8 hours on hour basis. The algorithm considered a week to be failed if voltage unbalance was higher than the limit for 8 times during a week. In other words, if 8 out of 168 hours were higher than the 2% limit. If a week was considered as failed, the failed hour counter was switched to zero.

The voltage unbalance was considered on the 95th percentile level. As it was discussed before, the 95th percentile value can be considered as worst case scenario. The remaining 5% values have sufficiently small probability to happen and they can be neglected. The numbers presented are a sum of voltage unbalance violations within a grid. In other words, the number is a sum of all violations on all the busses.

Table 9: Voltage unbalance violation count as per EN 50160

Number of weeks with VU violations over a season					
Region 1 (PR)	PV HC	Winter	Spring	Summer	Autumn
Strategy 0	25 %	0	2	0	0
	75 %	23	30	29	25
	125 %	23	34	30	26
Strategy 1	25 %	3	8	7	4
	75 %	40	44	36	29
	125 %	44	46	36	29
Strategy 2	25 %	0	0	0	0
	75 %	23	23	14	11
	125 %	31	25	14	12
Strategy 3	25 %	0	0	0	0
	75 %	75	39	19	19
	125 %	99	63	22	45
Region 2 (IN) Strategy 3	25 %	0	0	0	0
	75 %	20	10	0	10
	125 %	29	10	0	10
Region 3 (PU) Strategy 3	25 %	0	0	0	0
	75 %	8	4	0	4
	125 %	10	5	0	5

At strategy 0 and 25% HC, the voltage unbalance is violated twice during the Spring. However, at 25% and 75% HC, the voltage unbalance is violated 20-30 times per season. At strategy 1 and 25% HC, voltage unbalance is violated less than 10 times per season, in case of 75% HC - 45 times per season and in case of 125% HC - 50 times per season. At strategy 2 and 25% HC, voltage unbalance has no violations. At 75% and 125% HC violation count peaks 31 during Winter. Note, that strategy 2 has lowered violation count at Summer and Autumn, but increased at Winter. At strategy 3 and 25% HC, voltage unbalance limit is not violated. At 75% and 125% HC, violation count reach almost 100 times in winter and 22 times in summer.

In region 2, the voltage unbalance is being violated only at strategy 3. The violation starts at 75% HC and can reach up to 29 times per season at 125% HC. In region 3, voltage unbalance is violated few times at 75% HC and up to 10 times per season at 125% HC.

4.2.3 Voltage Unbalance probability distribution function

In this section, the probability distribution function will be presented. One page is dedicated to one region. Each page has four graphs - one for every strategy. Different colours represent four different seasons. The 95$^{\text{th}}$ percentile line was added to the plots for better readability of a graph. The probability distribution function was calculated at 125% HC level as the worst case simulated.

On Figure 12, the probability distribution function of region 1 is presented. In case of strategy 0, the 0% voltage unbalance has very high probability to happen. The winter has the lowest probability of voltage unbalance and summer and spring has the highest. At strategy 1, the 95$^{\text{th}}$ percentile value hits 2%-3% of voltage unbalance. The zero unbalance is less probable to happen. At strategy 2, the 95$^{\text{th}}$ percentile value is around 1.3%-1.8% and finally at strategy 3 - the 95$^{\text{th}}$ percentile value corresponds to voltage unbalance of 1.75%-2.25%.

On Figure 13, the probability distribution function of region 2 is presented. At strategy 0, all the values are below 2% limit of the voltage unbalance. The 95$^{\text{th}}$ percentile value lays between 0.5%-1% of voltage unbalance. Zero unbalance has a probability to occur at winter with probability of 80% and at summer 50%. At strategy 1, the 95$^{\text{th}}$ percentile lies between 0.7% and 1% of voltage unbalance, at strategy 2, between 0.5% and 0.7%. At strategy 3, the winter turns to be the worst season having the 95$^{\text{th}}$ percentile around 2%. Other seasons lay between 0,9% and 1.3% of the voltage unbalance.

On Figure 14, the probability distribution function of region 3 is presented. In region 3 the voltage unbalance is below 2% for all the times, except for strategy 3. At strategy 3, the 95$^{\text{th}}$ percentile value up to 1.5% of voltage unbalance during the winter and in rare occasions the voltage unbalance can reach even higher values.

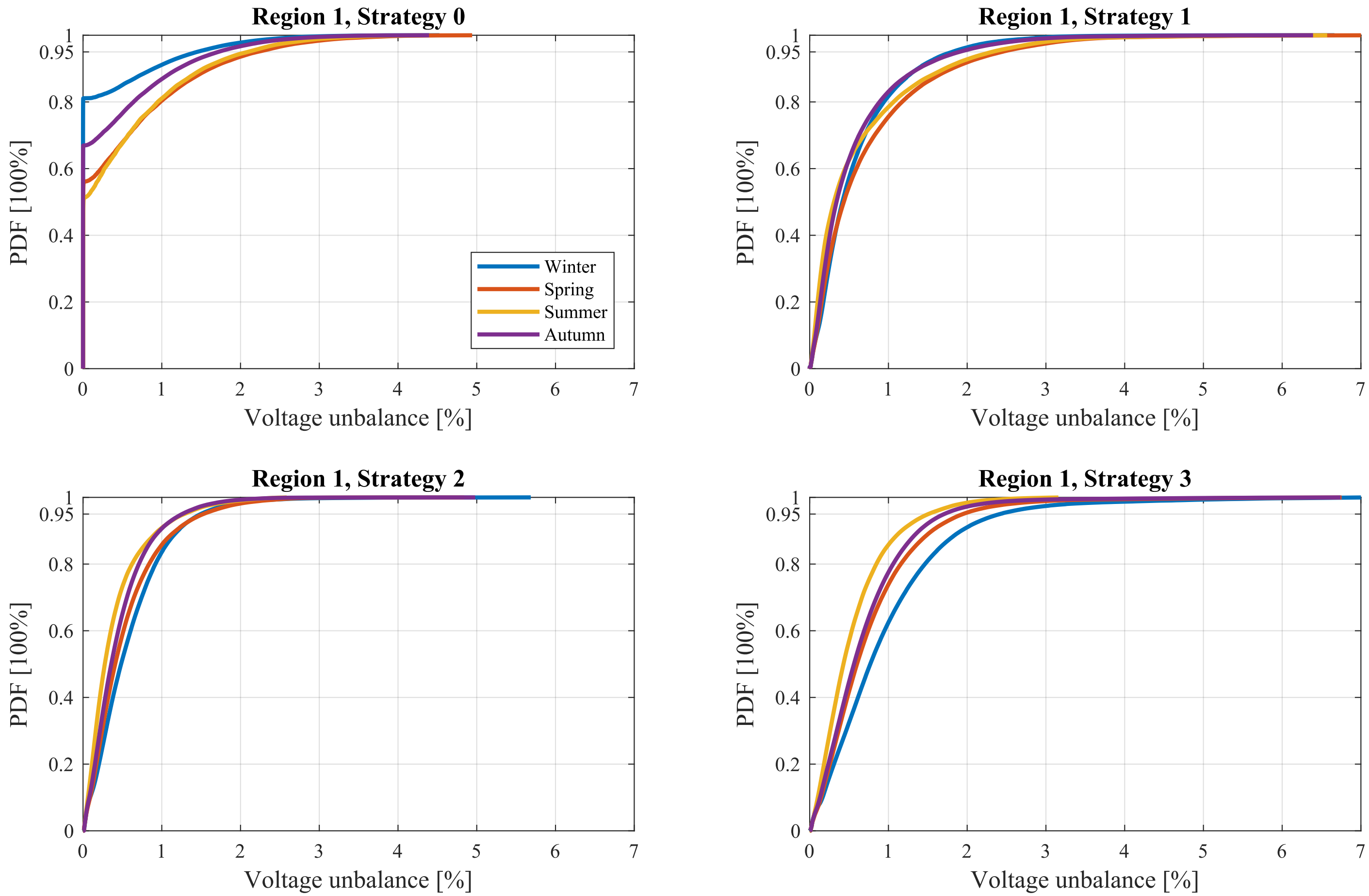

Figure 12: Probability distribution function of voltage unbalance - PR

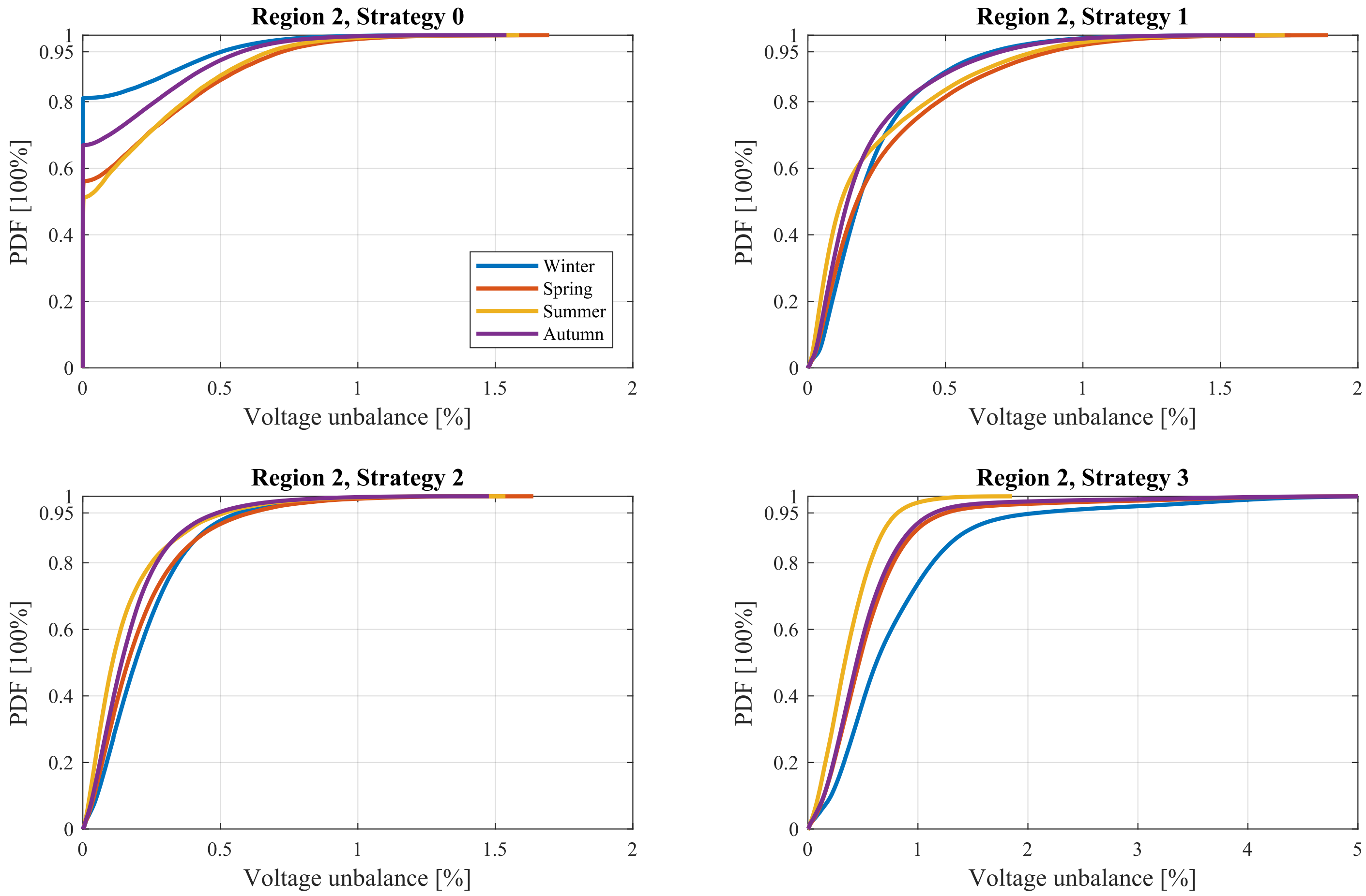

Figure 13: Probability distribution function of voltage unbalance - IN

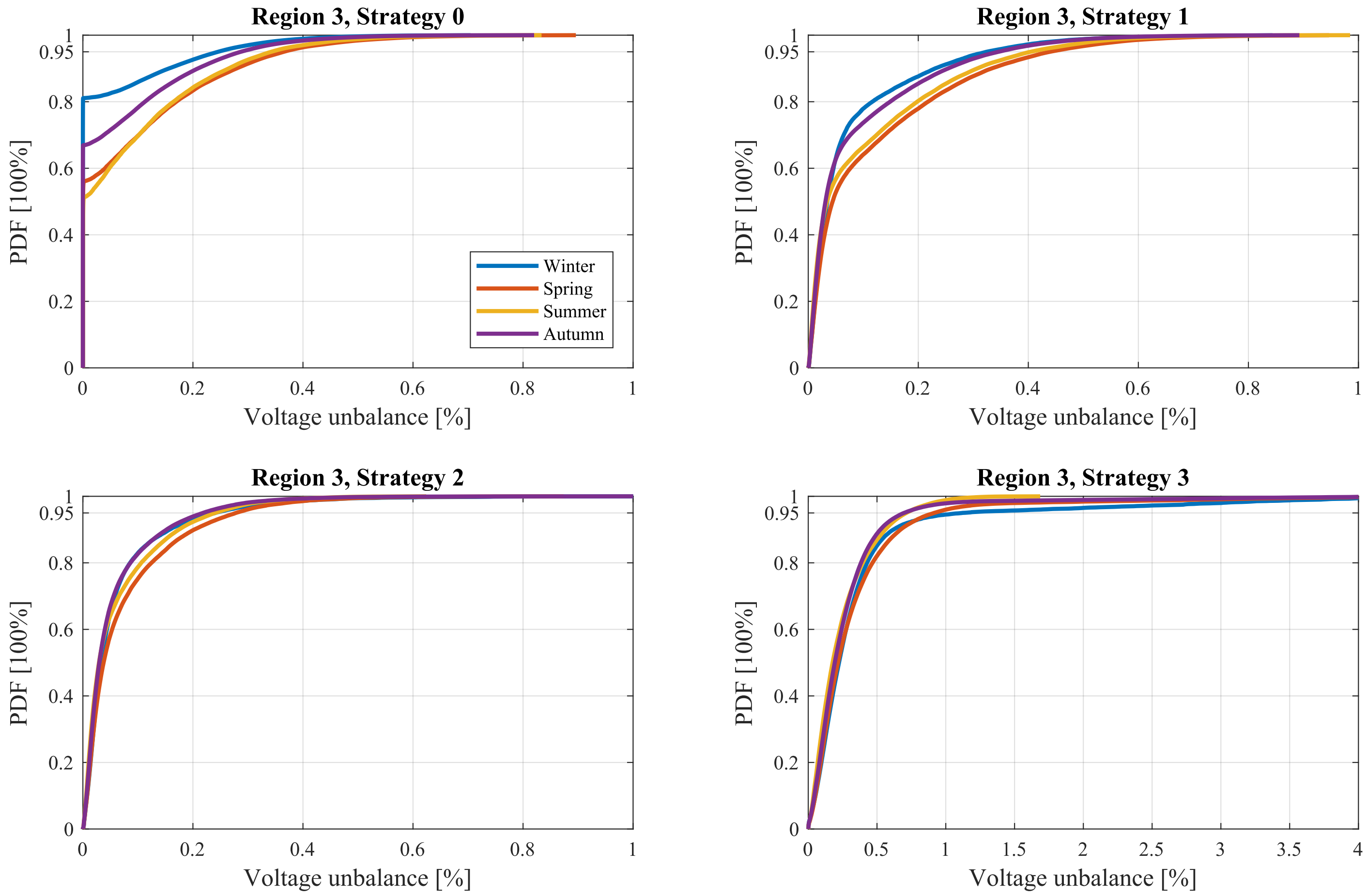

Figure 14: Probability distribution function of voltage unbalance - PU

5 Conclusions

In this section, the comments upon the thesis objectives will be given. Section is divided into three parts, each discussing an objective stated in the introduction section. A suggested reasons will be given for every topic discussed.

5.1 Stochastic voltage unbalance assessment algorithms

Stochastic voltage unbalance assessment method was developed based on Monte Carlo Simulation technique. Within the technique random values of solar array and battery quantity, location and phase connection were generated. The technique was applied for two algorithms: the time independent and time dependent. Both algorithms used same technique with small changes in loop construction. The results of both algorithms are three dimensional sets of voltage unbalance values at different busses at every iteration. The statistical method of the 95$^{\mathrm{th}}$ percentile percentile was applied.

The time independent algorithm has an advantage over time dependent in terms of simulation time. No matter how big is the grid, a time independent model can calculate voltage unbalance in reasonably short time: 5-60 minutes. The results of the algorithm will contain voltage unbalance values at every possible number of solar arrays in a grid.

Nevertheless, the time dependent algorithm has it's advantages over time independent algorithm. The time dependent algorithm can calculate voltage unbalance at every hour or whatever time increment it is being given. This allows to analyse a day or any other time span more comprehensively. It allows to find when are the highest voltage unbalance peaks present and what are their reasons. In addition to that, voltage unbalance can be analysed in case of occasional events, such as holidays. The results have better representation over seasonal voltage unbalance levels and number of voltage unbalance violations can be calculated. However, due to the fact, that algorithm needs to cycle through every time increment for 100 times, the time it takes to finish the simulation is quite long. Simulation of the biggest grid - the urban grid - can take up to 14 hours, which is long enough time to become a significant factor.

5.2 Time independent vs. Time dependent results

By examining the figures of time independent algorithm and tables of time dependent algorithm, it can be seen, that results of two algorithms are not matching. Results are in same magnitude and have similar trends, but the voltage unbalance values do not have reasonably close numbers.

The results of time independent algorithm are showing higher voltage unbalance values, than time dependent algorithm. One of the reasons behind this are the constant power models of time independent model. Solar array and battery are assumed to deliver rated power "at all times". On the other hand, the time dependent model solar generation changes between zero and rated power over time, decreasing the mean value. In addition to that, the battery power changes according to the load demand and solar generation. Battery power charges or supplies as much power as needed, which is usually less than the rated power.

By examining the time independent algorithm results, it can be noticed that voltage unbalance value growth rate slows down by increasing number of solar arrays. The values tend to saturate, however they do not stop at one value. Instead, voltage unbalance continue to grow slowly. Explanation for this can be found in three phase system. As more solar arrays being added, the probability of them being added to same phase falls drastically. By adding one solar array to a node, it's contribution to voltage unbalance is getting smaller as the number of solar arrays grow. It will be balanced out by other solar arrays. It can be clearly seen in region 3 (predominantly urban) grid, Figure 10.

The voltage unbalance values are smaller in bigger grids. It can be noticed by examining both time independent and dependent algorithm results. The voltage unbalance values are high in region 1 (predominantly rural) grid, being over the 2% limit in many cases. However, region 3 has voltage unbalance values never over 2%. Two main reasons can explain that. Bigger grid has more nodes per bus, which means that more solar arrays and batteries can be connected to voltage unbalance assessment point. As it was discussed above, the more imbalance sources are connected to one node, the less is the voltage unbalance. Another key factor of lower voltage unbalance is the feeder and transformer impedances. The feeder impedance of dense grids are lower due to thicker cables. There is smaller mutual impedance between busses and thus lower voltage unbalance. Another key factor of lower voltage unbalance in bigger (predominantly urban) grid is the low probability of customers with high load values (storage heated and direct electric heated). Most of the customers have district heating with low and relatively stable electricity demand.

The time dependent algorithm result allows to find the differences of voltage unbalance within different seasons. As it can be seen on voltage unbalance peak tables and probability distribution functions, the voltage unbalance of spring and summer is higher than during autumn and winter. The high solar generation in spring and summer cause high voltage unbalance. It can be clearly seen on probability distribution function graphs, where spring and summer are lower most curves. The day is long and the temperature is low at summer and spring, which makes solar generation efficient. During the rest of the year, solar generation is being compensated by higher heating demand of the customers. Moreover, Table 9 shows how many times was voltage unbalance violated in the grid. At strategy 0 (solar only), the voltage unbalance is being violated the most at spring and summer. However, at other strategies, the winter is leading in violation count. Due to big heating demand in winter and supplying the need for heating from battery, the voltage unbalance is kept high. The power of the battery is higher, than that of solar array, which makes voltage unbalance levels quite severe. Despite the lower peak values, voltage unbalance is present more often during winter.

By comparison with [31], the results of region 1 at strategy 0 are being validated. In the time independent algorithm, Figure 8, the voltage unbalance at 125% (128.9% in [31]) is significantly higher than the 2% limit. The simulation in [31] is based on time series load demand, so the results should be compared with time dependent algorithm results. The Table 5 shows the peak values are higher than the limit already at 25% HC. At 125% HC, the limit is exceeded on a grid level. In Table 9, the violation count is quite similar at 75% and 125% HC. The number of solar arrays is close in these cases and the table indeed shows that voltage unbalance is limiting the capacity of a network. The Figure 12 shows, that in winter and autumn the 95$^{\text{th}}$ percentile value is slightly below 2% and during summer and spring - slightly higher. The average value lies somewhere in between - around 2% of the voltage unbalance, which matches the result presented in [31].

5.3 Voltage unbalance mitigation

The aim of this thesis was to present voltage unbalance mitigation possibilities with energy storage battery system. The battery was connected in three different ways as per strategy chosen. By examining all the results of both algorithms, the strategy 1 - connecting battery to random phase - increases the voltage unbalance levels in a grid. The increase can be quite drastic and create voltage unbalance limit violations in a faultless grid. The strategy 2 - connecting battery to the same phase - has a good voltage unbalance mitigation efficacy. It can reduce voltage unbalance peaks and decrease the voltage unbalance to safe level at problematic busses.

The, strategy 3 - connecting battery to phase with highest voltage - has shown questionable results. In the results of time independent algorithm, the voltage unbalance was mitigated well at low number of solar arrays, even better than strategy 2. At high number, the voltage unbalance tend to increase linearly. While strategy 2 result approached one value, the strategy 3 voltage unbalance continued to increase. Nevertheless, in tested grids, the voltage unbalance levels of strategy 3 stayed below the limit.

In time dependent model, strategy 3 makes voltage unbalance higher during the seasons with high battery activity - winter - due to high heating power demand, which is being supplied by the battery. The supplied power has an effect of increasing the voltage, thus every next battery will be connected to the same phase as the other batteries, leading to high voltage unbalance. This could be solved by connecting the battery to the phase with lowest voltage instead, while battery is supplying the grid. Still, during the seasons with low battery activity - summer - the voltage unbalance is being mitigated well, similarly to strategy 2.

The author of the thesis would like to emphasise the importance of power flow management of the battery. The voltage unbalance mitigation by battery is much more than choosing the right connection phase. Battery should be controlled by a power sharing algorithm, which would consider the power quality aspects. As it was showed in the results of time dependent algorithm, the battery can increase the levels of voltage unbalance, if the battery power will not be constrained by some additional parameters.

6 Discussion

In this section, some aspects relevant to the research done in this thesis will be discussed. New ideas for optimisation of the model and future work will be brought up.

6.1 Monte Carlo Simulation convergence

One of the key ideas of Monte Carlo Simulation is the repetitiveness and random generation of values at every iteration. The more iterations a model does, the more values in results will be available for analysis. However, having large number of iterations have a payback in terms of calculation time. Finding the right balance between iteration number and calculation time is a key thing in Monte Carlo Simulation models.

In this research, iteration numbers were chosen randomly. Numbers, that felt big enough, were chosen: 1000 iterations for time independent algorithm and 100 for time dependent. In the continuation of the research, the iteration numbers could be chosen automatically by assessing the mean value change. At the every iteration the mean value of the result can be compared to the mean value at the previous iteration. The simulation can be finished, if the mean value difference will be considered small enough. The mean value difference can be chosen in such a way that it would satisfy the precision requirements.

6.2 Solar array size impact on the voltage unbalance

The single solar array size can have a significant impact on voltage unbalance levels in a grid. Bigger solar array have higher power output and thus higher current imbalance. However, that is not the case how solar generation in a grid is measured. The solar generation is measured as hosting capacity, as it was done in this thesis, or as a solar generation relation to feeding secondary transformer or in any other relation.

Sometimes the voltage unbalance assessment can be confusing, because at the same hosting capacity values, the voltage unbalance can be different. Hosting capacity can be interpreted as a number of solar arrays multiplied by the power of a single solar array. Having small number of high power solar arrays (or batteries) can lead to higher voltage unbalance levels, than high number of low power generators. This is the reason why some distribution system operators have a power limit for connected single-phase distributed generator, solar arrays are not an exception. In order not to create confusion, one should mention the power of a single solar array while speaking about hosting capacity of a grid.

6.3 Hosting Capacity vs. PV penetration

In stochastic models, such as developed in this thesis, the load values are usually probabilistic. They are defined by probability functions or deterministic load value is assigned to a node by some probability. Before the total demand power in a grid could be calculated, the load values are needed to be assigned to a node. The load are being assigned at every iteration, which ends up having different load values and thus different number of solar arrays at every iteration.

Hosting capacity parameter could be substituted with PV penetration in stochastic models. PV penetration is a rigid number, which depends on secondary transformer power rating of a grid and it remains constant during all the iterations. The hosting capacity gives a better representation about the power balance in a grid and power quality, though. However, utilising PV penetration parameter would keep the number of solar arrays the same at every iteration.

6.4 Load and background voltage unbalance

The distribution system is hardly ever symmetrical. Many small single-phase loads being connected to the grid without ever coordinating with phase. Nevertheless, in this thesis, the loads were assumed to be symmetrically divided between phases and not causing any voltage unbalance. This was done in order to simplify the model. However, feature of unsymmetrical load could be added in future research.

Load asymmetry could be generated within a Monte Carlo Simulation. Usually, the smart meter data keeps the track of consumed energy, which is then converted to average power. The power is assumed to be equally distributed between three phases. However, in order to gain required voltage unbalance, the power values could be changed. The required load voltage unbalance could be generated based on probability distribution function.

The source for the voltage unbalance in distributed grid can be the secondary transformer. Secondary transformer connects distribution grid with medium voltage transmission grid. The voltage unbalance created upstream from distribution grid can be called background voltage unbalance and it can be added to the results of the simulation. While modelling the background voltage unbalance, it’s magnitude can be based on probabilistic model as well.

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A Input Data

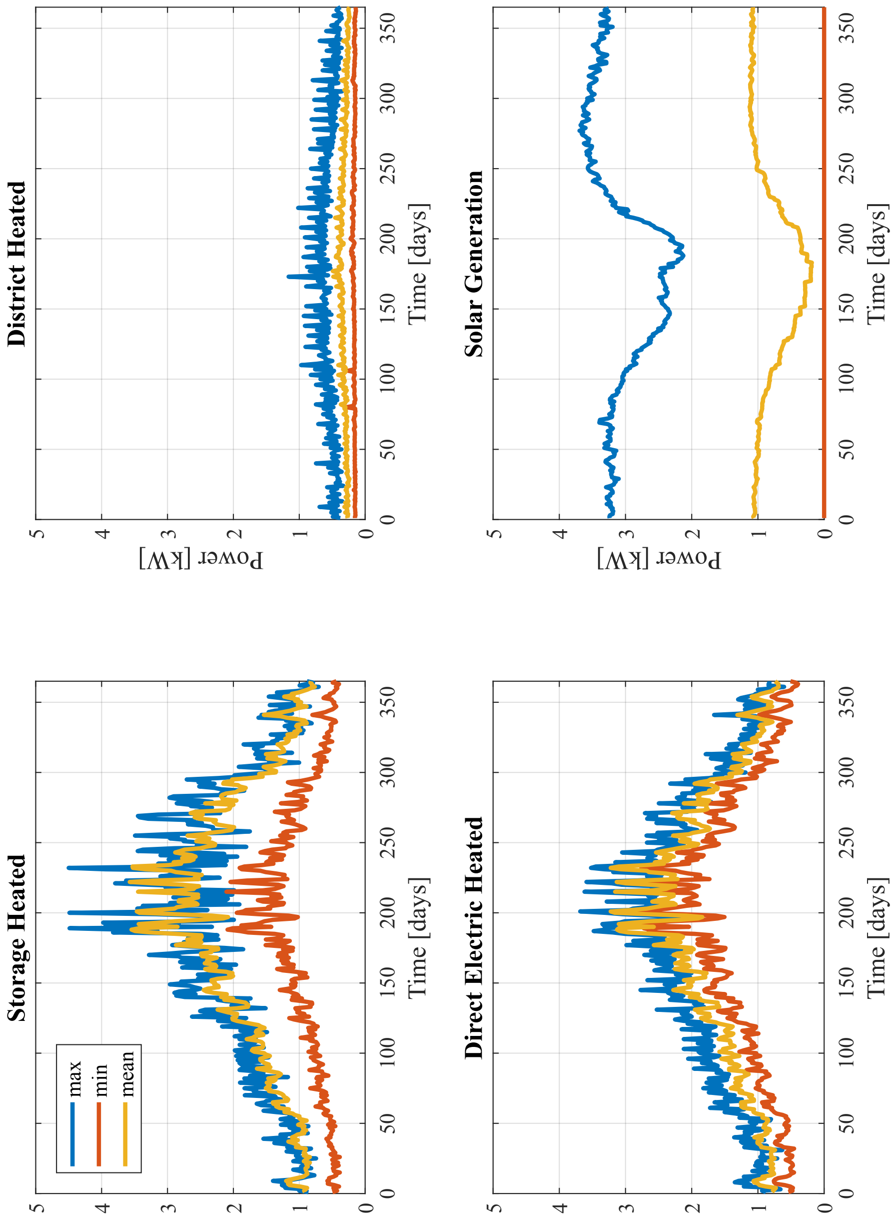

Figure A1: Daily Power Values - 1st July 2008 - 30th June 2009